**Ph.D. Research Proposal**

**Doctoral Program in "Department Name"**

# Optimized MAC Scheduling for URLLC in Industrial IEEE 802.11ax Communication

**by**

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## 1. Introduction

IEEE 802.11ax is an evolution of WLAN which aims to improve bandwidth efficiency and latency for future WLANs [1], [2], [11]. Ultra reliable low latency (URLLC) wireless systems art dedicated to communications such as factory automation, mission control applications, healthcare applications etc. which requires minimum latency [3]-[5]. In industrial sensor network optimal routing algorithm is significant in order to achieve minimum latency [7], [15]. An energy efficient QoS aware routing protocol was proposed for industrial sensor network [6]. Here data transmission through multiple paths increases data loss which affects the reliable transmission. A delay aware routing protocol uses hopcount as routing metric in industrial network [13]. However, route selection based on single routing metric is not effectual and also network scalability is poor. In cross-layer based routing for WLANs, Dijkstra algorithm was adapted [14]. In general, Dijkstra algorithm involves with large time consumption which degrades the network performance. Many works such as NSPBS [8], D-ALOHA [10], and iQRA [12] were held on MAC scheduling for achieving URLLC communication in IEEE 802.11ax. Here NSBPS is not able to utilize resources in an effective manner for URLLC. D-ALOHA is not able to support large number of nodes and iQRA is not significant since channel observation state only considered. In addition, all above scheduling scheme are not able to consider emergency level of data which plays significant role in industrial networks. For enabling URLLC communication, massive multiple input multiple output (MIMO) antenna was utilized [9]. In MIMO communication optimal antenna selection is major problem which increases interference as well as latency.

## 2. Problem Statement

GA based optimal antenna selection was proposed for MIMO networks in order to maximize throughput in the network [16]. However, objective function formulation by considering throughput metric alone is not efficient. In addition, time consumption for antenna selection is increased since GA is used. PE-MAC and OPE-MAC scheduling schemes were

proposed to enable priority based MAC scheduling for URLLC [17]. Here priority is given for nodes instead of data (i.e.) emergency data from low priority nodes experiences large delay. Furthermore, allocation of slot for retransmission leads to resource underutilization. In industrial automation, URLLC is enabled by grouping nodes in the network [18]. Group formation which is major process is not involved with significant criteria. Leader node selection is also not efficient for industrial network. A two-level MAC scheduling was proposed for URLLC communication in 5G wireless networks [19]. Scheduling based on deadline increases delay for emergency data which is not desired for efficient networks. This two-level MAC scheduling is not able to support large number of nodes. In URLLC communication, joint link adaption and scheduling was performed to minimize latency [20]. Here latency for URLLC is minimized in the cost of throughput degradation for eMBB communication. MIMO is used to achieve minimum latency. However, data transmission through non optimal antenna increases latency and data loss in the network. Thus reliable data transmission with minimum latency is still major challenging issue in industrial network.

## 3. Proposed work

To overcome abovementioned problems we proposed a novel Priority Aware MAC scheduling scheme for IEEE 802.11ax based industrial sensor network. Our network comprises following entities: sensor and actuator nodes with single input single output (SISO) antenna, and base station (BS) with MIMO antennas. All sensor and actuator nodes are deployed in the industrial environment and communication among them is enabled by IEEE 802.11ax. To achieve, URLLC in IEEE 802.11ax network, we perform following processes: (i) cluster formation, (ii) intra-cluster routing, (iii) MAC scheduling, and (iv) optimal antenna selection.

### 3.1 Cluster formation

Initially the network is divided into multiple clusters in order to minimize number of terminals reporting to BS. For cluster formation, Optimal K-Medoids Clustering with Optimized Size **(OKMC-OS)** algorithm is proposed. Here weight value is computed based on *remaining energy level, distance with BS, average distance with other nodes, and node degree*.

### 3.2 Intra-cluster routing

To enable reliable data transmission within each cluster, optimal intra-cluster routing algorithm is proposed. For intra-cluster routing, a novel **Hybrid Hydrological Optimization (H2O)** algorithm is proposed. Route selection game considers energy level, link quality, and delay for optimal next hop selection.

### 3.3 MAC scheduling

To achieve low latency without loss in throughput, we propose a novel **Multi-Level Priority aware MAC scheduling (ML-PMAC)** protocol. In ML-PMAC protocol, priority for each data packet is determined *by* ***Capsule Network (CAP-NET)*** based on significant packet features. Then, scheduling is performed by ***Adaptive Earliest Deadline Scheduling (AEDS)*** algorithm. ML-PMAC protocol is performed by CH in order to transmit data to MIMO-BS.

### 3.4 Optimal antenna selection

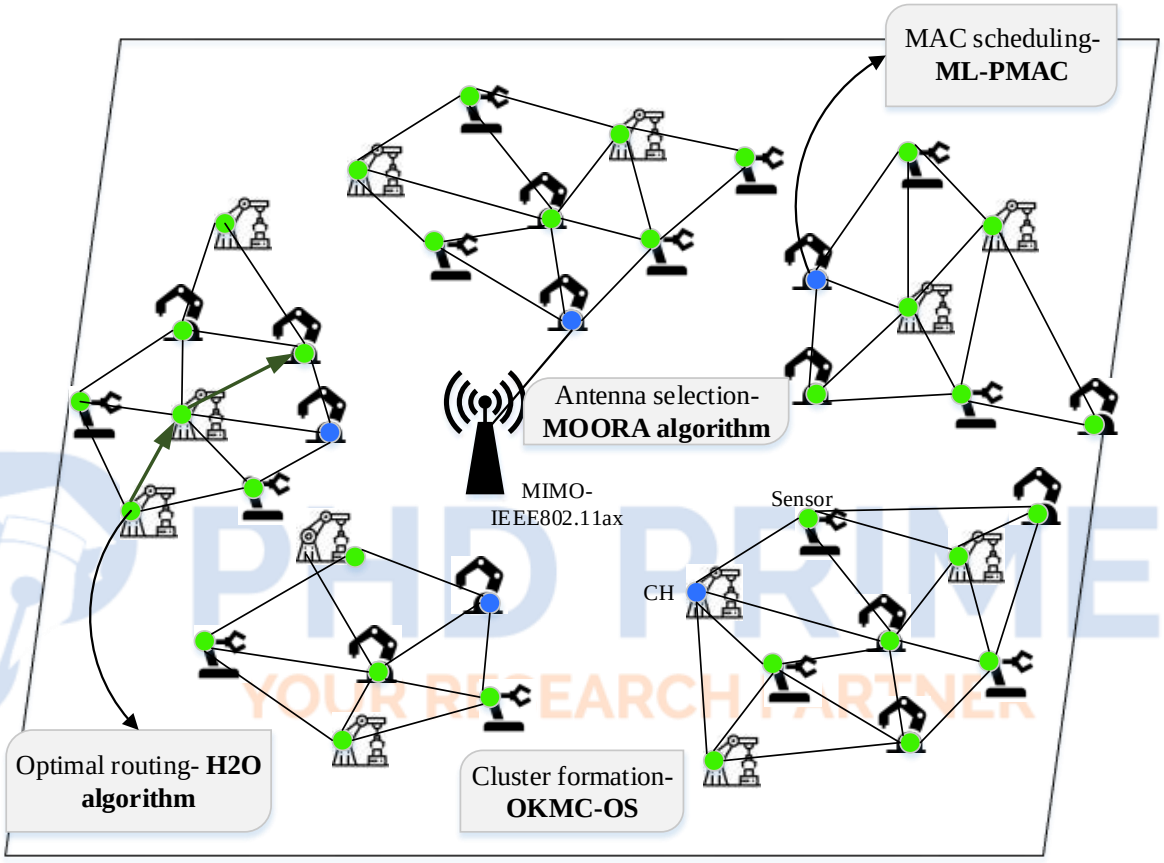
In MIMO-BS, optimal antenna selection is challenging issue which improves the efficiency of the data transmission. Optimal antenna selection is performed by using **MOORA** algorithm. In MOORA algorithm, fitness value is formulated by considering signal to noise ratio (SNR), channel state information (CSI), and channel capacity.

Thus our proposed work achieves better throughput with minimized latency in IEEE 802.11ax network for industrial applications. In our work, involvement of cluster formation, intra-cluster routing, MAC scheduling, and antenna selection improve network throughput without increase in latency. Finally our proposed work is evaluated in terms of following performance metrics,

- Throughput with respect to number of nodes
- Throughput with respect to packet arrival rate
- URLLC latency with respect to number of nodes
- URLLC latency with respect to packet arrival rate
- Packet delivery ratio (PDR)

- Packet loss rate
- Average energy cosnumption

## Overall Architecture



## Paper Explanation

### Paper 1

**Title:** On Quality-of-Service Provisioning in IEEE 802.11ax WLANs

### Concept

IEEE 802.11ax is a significant improvement of IEEE 802.11 which is approved to deliver the next-generation WLAN technologies. The major objective of 802.11ax is to improve bandwidth efficiency, latency, long term evolution, and licensed access. Typically, IEEE 802.11ax addresses the collaboration between cellular and WLANs and given trend of 5G cellular over unlicensed bands. IEEE 802.11ax is provided with 2.4/5GHz of bandwidth and planned to achieve data rate upto multiple terabytes.



### Paper 2

**Title:** IEEE 802.11ax: High-Efficiency WLANs

### Concept

IEEE 802.11 is wireless local area network (WLAN) which is cost-efficient solution for wireless internet access. The significant evolution of 802.11 is IEEE 802.11ax which is a high efficiency WLANs. Evolution of WLANs includes latest technologies and scenarios such as cognitive radio, long range communication, advanced power saving, and support for machine type communications. IEEE 802.11ax is considered as next generation WLANs that resolves the problem of user experience and performance degradation in WLANs.

### Paper 3

**Title:** Energy Efficiency and Delay in 5G Ultra-Reliable Low-Latency Communications System Architectures

**Concept**

Ultra reliable low latency communication (URLLC) wireless systems are characterized to have minimum latency. URLLC is major service in fifth generation (5G) network along with enhanced mobile broadband (eMBB) and massive machine type communication (mMTC). According to third generation partnership project (3GPP) the major requirement of URLLC is to minimize the latency without loss in packet reception.

**Paper 4**

**Title:** Resource Allocations for Ultra-Reliable Low-Latency Communications

**Concept**

URLLC feature is essential for supporting envisioned mission-critical applications, especially for machine type communications. These applications require low latency for data transmission. To improve reliability and to minimize latency this paper proposes a resource allocation scheme for URLLC communication. In order to take advantages of data retransmissions, a reliable feedback channel is suggested.

**Paper 5**

**Title:** Optimum Ultra-Reliable and Low Latency Communications in 5G New Radio

**Concept**

Tradeoff between latency and reliability is a significant as well as critical requirement of URLLC. To achieve better transmission rate, this paper proposes a multi-armed bandit (MAB) based reinforcement learning approach. Queue management is realized as M/G/1/∞ queue. The reinforcement algorithm is proposed for optimum harmonization of URLLC and URC data with retransmissions.

**Paper 6**

**Title:** An Energy Efficient and QoS Aware Routing Algorithm Based on Data Classification for Industrial Wireless Sensor Networks

**Concept**

This paper deals with quality of service (QoS) aware routing in industrial wireless sensor network. For that an energy efficient and QoS aware (EEQA) routing algorithm is proposed for industrial network. In this algorithm data classification is performed based on three attributes such as high timeliness event data, low timeliness event data, and periodic data. Then based on data category, priority level is given for each data. Based on priority level, data is scheduled and multipath routing is performed.

**Problems**

- Data transmission through multiple paths leads to data loss

**Proposed Solution**

- Data transmission is performed through optimal route selected by H2O algorithm based on multiple criteria

**Paper 7**

**Title:** Directional Link Scheduling for Real-time Data Processing in Smart Manufacturing System

**Concept**

This paper presents a new directional routing and link scheduling algorithm to minimize latency and to improve throughput in smart manufacturing network. For link scheduling, maximum weight independent set (MWIS) algorithm is proposed to reduce the latency in the network. In addition, direction backhaul routing is enabled among edge nodes in order improve data transmission.

**Paper 8**

**Title:** Opportunistic Spatial Preemptive Scheduling for URLLC and eMBB Coexistence in Multi-User 5G Networks

**Concept**

This paper proposed a null-space based preemptive scheduler (NSBPS) for joint eMBB and URLLC traffic. Here low latency for URLLC traffic is achieved by using capacity of eMBB slice in the network. So that URLLC traffic experiences no or minimum queuing delay during data transmission. In this paper, transmission delay and queuing delay are considered as major delay for URLLC traffic and delay for URLLC traffic is minimized by utilizing resources of eMBB traffic.

**Problems**

- However, this method is not able to utilize resources of URLLC communication for achieving low latency.
- Scheduling is performed without considering emergency level of the data



**Proposed Solution**

- Low latency is achieved by optimal routing and priority aware MAC scheduling in URLLC
- TP-PriorMAC scheduling determines priority level of packets by CAP-NET algorithm by considering multiple packet features

**Paper 9**

**Title:** Ultra-Reliable and Low Latency Communication in mmWave-Enabled Massive MIMO Networks

**Concept**

This paper attempts to achieve URLLC in (millimeter wave) mmWave enabled massive MIMO networks. To achieve minimized latency, a utility based delay control approach which adapts to channel variations, and queue dynamics is proposed. The reliability and latency in the network is formulated as NUM problem and solved by considering latency/reliability constraint and QoS/rate requirement constraint in Lyapunov control approach.

**Problems**

- Here data transmission through optimal antenna is major problem since interference and antenna selection are significant problems in MIMO networks

**Proposed Solution**

- Optimal antenna selection is performed by MOORA algorithm which results in reliable data transmission

**Paper 10**

**Title:** Martingales-based energy-efficient D-ALOHA algorithms for MTC networks with delay-insensitive/URLLC terminals co-existence

**Concept**

This paper proposes energy efficient differentiated ALOHA (D-ALOHA) random access algorithm to support URLLC for machine type communication. D-ALOHA algorithm achieves energy efficiency as well as requirements of URLLC through distributed manner. In addition, delay QoS problem is resolved by invasive weed optimization-differential evolution (IWO-DE) algorithm.

**Limitation**

- The proposed D-ALOHA algorithm supports only small number of nodes in the network

**Proposed Solution**

- Proposed work supports large number of nodes since it manages large network through optimal cluster formation

**Paper 11**

**Title:** IEEE 802.11ax: Highly Efficient WLANs for Intelligent Information Infrastructure

**Concept**

This paper provides an overview on IEEE 802.11ax which is next generation WLAN technology. IEEE 802.11ax is aimed to fuel the future intelligent information infrastructure to serve big data transportation and diverse smart applications. The main features of IEEE 802.11ax are orthogonal frequency multiple access (OFDMA) physical layer, multi user MIMO, spatial reuse, OFDMA random access, and power saving.

**Paper 12**

**Title:** Deep Reinforcement Learning Paradigm for Performance Optimization of Channel Observation-Based MAC Protocols in Dense WLANs



**Concept**

In this paper, deep reinforcement learning (DRL) based MAC scheduling algorithm is proposed for dense WLAN networks. Here IEEE 802.11ax WLAN network is utilized and Q-learning is adapted as DRL. An intelligent QL-based resource (iQRA) algorithm is proposed for MAC layer channel access in dense WLANs. For channel observation, a distributed coordination function (DCF) approach is proposed. Based observed channel state, scheduling is performed in the network.

**Problem**

- Here resource allocation (i.e.) scheduling is performed based only on channel observation state. The significant parameters are not considered in this work for channel allocation
- The MAC protocol is not able to consider emergency level of data

**Proposed Solution**

- Proposed TP-PriorMAC protocol is performed based on multiple criteria including priority level of data

**Paper 13**

**Title:** A Delay-Aware Wireless Sensor Network Routing Protocol for Industrial Applications

**Concept**

This paper presents an optimal routing algorithm for industrial sensor networks in order to minimize transmission delay. This paper uses geographic routing and all information are stored in routing table of each node. Then the optimal route selection is performed based on hop count (i.e.) the node which is nearer to destination is selected to establish optimal route between source and destination.

**Problems**

- Optimal route selection by considering single metric (hopcount) is not efficient in industrial networks
- The number of terminals reporting to base station is increased which results in large delay in the network.

**Proposed Solution**

- H2O based optimal route selection considers multiple metrics to improve throughput and to minimize latency
- The number of terminals reporting to BS is minimized by OKMC-OS based cluster formation which further results in minimum latency

**Paper 14**

**Title:** Cross-layer selective routing for cost and delay minimization in IEEE 802.11ac wireless mesh network

**Concept**

In this paper a cross layer based routing protocol is proposed for WLAN networks. In this paper, wireless internet-access mesh network is designed with multiple access points and gateways to achieve scalability and reliability. For optimal routing, a selective routing algorithm based on Dijkstra algorithm and 2-opty algorithm is proposed. In route selection algorithm, optimal route is selected based on end-to-end delay in order to minimize transmission delay.

**Problems**

- Dijikstra based routing increases time consumption for route selection and also fails to select optimal route since route selection relies on single metric

**Proposed Solution**

- H2O based optimal route selection selects best route for data transmission without increase in time consumption

**Paper 15**

**Title:** Performance analysis of ultra-reliable short message decode and forward relaying protocols

**Concept**

This paper evaluates the performance of three cooperative routing schemes such as dual hop decode and forward, selection combining, and maximum ratio combining schemes for URLLC communication. These schemes are evaluated under two strategies such as with equal power allocation and optimal power allocation strategies. This analysis shows that none of these schemes provides improvement in latency as well as in throughput jointly. Thus optimal routing algorithm is necessary to achieve URLLC communication.

**Paper 16**

**Title:** A Genetic Algorithm-based Antenna Selection Approach for Large-but-Finite MIMO Networks

**Concept**

This paper proposes genetic algorithm (GA) based optimal antenna selection algorithm for MIMO networks. The proposed GA based antenna selection algorithm is generic model (i.e.) any objective function can be adapted in this algorithm. In this paper, achieving high throughput is formulated as objective function and upon this objective function optimal antenna selection is performed. The major aim of this paper is to overcome the problems involved in exhaustive search based antenna selection.

**Problems**

- Antenna selection using GA is time consuming process since typically GA requires large time for optimal solution determination
- The objective function formulation is not significant since throughput metric only considered.

**Proposed Solution**

- To minimize antenna selection time MOORA algorithm is proposed
- Fitness function in MOORA algorithm is formulated based on SNR, CSI, and channel capacity

**Paper 17**

**Title:** Dynamic Priority Based Reliable Real-Time Communications for Infrastructure-Less Networks

**Concept**

This paper proposes a priority enabled MAC scheduling (PE-MAC) and optimized PE-MAC (OPEC-MAC) scheduling schemes. The major objective of this paper is to ensure real-time reliable data delivery in emergency and feedback system. Here URLLC communication is

enabled in IEEE 802.15.4e networks. Initially the nodes are classified into low priority nodes and high priority nodes. Then the super frame is constructed based on priority level of nodes.

**Problems**

- Here priority is given for nodes instead of data. Thus emergency data from low priority nodes experiences large waiting time
- In each super frame, last slot is always allocated for retransmission in case of data loss. However, data retransmission is not always ensured

**Proposed solution**

- In our work, TP-PriorMAC protocol is proposed for scheduling in which priority for data is determined by CAP-NET algorithm.
- In proposed work, number of retransmission is minimized by H2O based optimal routing. Further, acknowledgement is used for retransmission. The data which has NACK only retransmitted

**Paper 18**

**Title:** A D2D-based Protocol for Ultra-Reliable Wireless Communications for Industrial Automation

**Concept**

In this paper, overall process is performed with in single cell of 5G network with URLLC communications. Here initially device-to-device network clusters are formed within the cell and two-phase transmission protocol is proposed to achieve URLLC. In first phase, BS multicasts the message to all devices in the network. The device which decodes the received message successfully is selected as cluster head (CH) and forms clusters with neighboring nodes. In second phase, the CH sends the message to all of its cluster members. The data transmission is performed through CH in order to achieve minimum latency.

**Problems**

- Here group formation is not significant and CH is selection is not optimal. But URLLC communication is implemented by group formation.
- Lack of effectual scheduling limits the performance of the network

**Proposed solution**

- OKMC-OS algorithm is proposed for cluster formation with optimal CH which improves the network performance and minimizes latency
- TP-PriorMAC scheduling improves performance of the network by considering priority for each data.

**Paper 19**

**Title:** Providing Low Latency Guarantees for Slicing-Ready 5G Systems via Two-Level MAC Scheduling

**Concept**

This paper uses software defined networking (SDN) for achieving URLLC services. Initially, the network is divided into multiple slices and in each slice scheduling is performed. For downlink transmission, earliest deadline first scheduling is performed and for uplink communication semi-persistent scheduler is proposed. Both scheduling schemes are performed based on deadline of data.

**Problems**

- Scheduling based on deadline only increases delay for high priority (emergency data) data
- Not able to support large number of nodes due to scalability constraints

**Proposed solution**

- Scheduling is performed by TP-PriorMAC scheduling protocol which determine priority of packets by CAP-NET
- Involvement of cluster formation supports vast number of nodes in the network

**Paper 20**

**Title:** Joint Link Adaptation and Scheduling for 5G Ultra-Reliable Low-Latency Communications

**Concept**

In this paper, link adaption and resource allocation is jointly performed to minimize latency for URLLC communications. Here latency in URLLC is minimized from 1.3ms to 1ms by minimizing 10% of throughput of eMBB communications. Radio channel aware packet scheduling is proposed and link adaption is performed based on channel quality indicator.

**Problems**

- Here low latency is achieved by reducing throughput of eMBB communication (i.e.) resource utilization is not effectual.
- Not able to minimizes latency for large size packets due to queue delay
- Perhaps MIMO is utilized in this method; absence optimal antenna selection limits the overall performance of the network.



**Proposed solution**

- Low latency is achieved through optimal cluster formation, routing, MAC scheduling, and edge computing without need of eMBB bandwidth
- Involvement of edge computing minimizes latency for all packets and scheduling is performed based on packet size
- Optimal antenna selection is performed by MOORA algorithm which improves the efficiency of the network

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