Criticality Aware Scheduler Prioritization in Virtual Orthogonal Multichannel Parallelism for 5G Cellular Network

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To fulfill various enhanced requirements of next generation wireless access, 5 G cellular network will drive towards higher energy efficiency, lower latency and higher reliable wireless networks. The key contributions can summarize as follows: (1) proposes frame-based max-weight scheduling (FMWS) with reconfiguration delay in combination of round-robin algorithm can dynamically control throughput and delay. The frame-based dynamic control (FBDC) policy is applicable to 5 G cellular network control systems in data link layer, provides a new framework for developing throughput-optimal network control policies using state-action frequencies. (2) proposes a novel approach in MAC layer--Virtual multichannels Parallelism Carrier Sense Multiple Access (VMCP-CSMA) which can compute a set of TDDM schedules for multiple channels at once rather than computing one schedule at a time and constantly switching or recomputing schedules. (3) proposes a novel criticality aware scheduler prioritization in VMCP-CSMA policy can reorder a set of TDDM schedules based on max-weight scheduling with reconfiguration delay according to different application requirements. It can achieve high throughput and low delay with low complexity compared with other schedulings.

• Networks→Network layer protocols→Routing protocols • Networks→Network algorithms→Data path algorithms→Packet scheduling • Networks→Network algorithms→Control path algorithms→Network resources allocation • Networks→Network algorithms→Control path algorithms→Network control algorithms

Key words: 5G cellular network, maximal scheduling, throughput-optimal control, virtual multiple channels, criticality aware scheduler prioritization.

1. INTRODUCTION

Next generation wireless access will support a much wider range of use case characteristics and corresponding access requirements [1]. To guarantee support for latency-critical machine-type-communication [2] (MTC) applications, 5 G wireless access should allow for latencies on 1 ms or less. In the future, new paradigm in 5 G cellular networks is full duplex cognitive radio with energy-efficient, low-latency and high-reliable. Promising network layer architecture of 5 G will adopt SDN, NFV and control-data separation technique [3]. One of key enabling technologies in 5 G Physical layer is Sparse Code Multiple Access (SCMA) [4], which could adapt the frame structure according to MAC payload. SCMA was proposed to allow complex entries in the signature matrix and each user enjoys a different codebook to avoid the coupling issues, which was considered as an energy efficient uplink approach for future 5 G wireless systems. Other transmission technologies such as frequency domain (millimeter wave [5-6]) or spatial domain (massive MIMO technology [7])

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or ultra dense network deployment) are to increase the radio resources. Cognitive radio (CR) network [8] is considered to be one of key promising components for next generation mobile network [7]. Interference-tolerant CR networks can achieve enhanced spectrum utilization by opportunistically sharing radio spectrum resources with licensed users, as well as better spectral and energy efficiency. 5G cellular network is developed towards energy-efficient [9], low latency and high reliable high mobility communication network.

With future deployment of Full duplex (FD) [10] systems, time division duplex (TDD) and frequency division duplex (FDD) will be harmoniously integrated, supporting all the half duplex mobile phones efficiently, leading to a much enhanced 5 G system performance. The maximal scheduling algorithm for multiradio multichannel (MR-MC) [11] wireless networks can obtain optimal throughput control and extend local pooling factor to analyze capacity efficiency in the tuple-based greedy maximal scheduling (GMS) in MR-MC networks. To guarantee high throughput and optimal capacity efficiency, the Tuple-based Dynamic Distributed Maximal Scheduling (TDDMS) algorithm is developed for contiguous enhanced services in 5G communication to fulfill these significant performance requirements. This paper proposes a novel criticality aware scheduler prioritization in virtual multichannel parallelism algorithm for future 5 G systems.

The reminder of paper is organized as follows. Section II proposes criticality aware scheduler prioritization in virtual multichannel parallelism algorithm for 5 G cellular network. Section III describes system model, algorithm description and implementation of CASP-VOMCP, Coordinated criticality-Aware Rate-function Acceleration (CARA) as well as performance metrics of proposed CASP-VOMCP. Section IV derives an upper bound and lower bound on the rate-function. Simulation results on throughput and capacity are presented in section V. Finally, conclusions are reiterated in section VI.

2. CRITICALITY AWARE SCHEDULER PRIORITIZATION IN VIRTUAL MULTICHANNEL PARALLELISM ALGORITHM FOR 5 G CELLULAR NETWORK

2.1 Variable Frame-based Max-Weight scheduling algorithm (VFMW)

Time-varying channels and reconfiguration delays significantly reduces the system stability region and changes the structure of optimal policies. Frame-based Max-Weight scheduling algorithm [12] that sets frame durations dynamically, as a function of the current queue lengths and average channel gains, is throughput-optimal. Characterizing the stability region of such system using state-action frequencies are stationary solutions to a Markov Decision Process (MDP) formulation. A dynamic control policy using the state-action frequencies and variable frames whose lengths are functions of queue sizes have proposed in [12] and show that it is throughput-optimal. The frame-based dynamic control (FBDC) policy is applicable to many network control systems, provides a new framework for developing throughput-optimal network control policies using state-action frequencies. Myopic policies are easy to implement and have better delay properties than FBDC. The network controller is to

dynamically decide to stay with the current schedule of activations or to reconfigure to another schedule based on the channel process and the queue length information, where each decision to reconfigure leaves the network idle for an arbitrary but finite amount of time, corresponding to the reconfiguration delay. FBDC policy based on state-action frequencies achieves the full stability region. Myopic policies may achieve the full stability region while providing better delay performance than FBDC policy for most arrival rates.

2.2 Optimal dynamic control policy with reconfiguration delays

The important task is the analysis of reconfiguration delays on system stability and throughput-optimal max-weight scheduling algorithm. In a parallel queuing system with randomly varying connectivity, characterizing the stability region of the system uses throughput-optimality of the longest-connected-queue scheduling policy. Variable-size Frame-based Max-Weight (VFMW) [12] policy provides a good balance by dynamically adapting the frame length based on the queue sizes and stabilizes the system whenever possible, while providing a delay performance that is similar to that of a Max-Weight policy with fixed frame sizes (FFMW) policy with a small frame length for small arrival rates. Scheduling under reconfiguration delays and time-varying channels call for novel control algorithms that take advantage of the channel memory to improve performance. Joint scheduling [13] and high-throughput routing [14] in multihop delay tolerant networks (DTNs) with time-varying channels and reconfiguration delays are essential for dynamic control-optimal policy by cross-layer optimization.

2.3 Delay-based server-side-greedy policy

Delay-based Server-Side-Greedy (D-SSG) [15] guarantees a near-optimal rate-function, delay performance to the rate-function, delay-optimal policy. D-SSG allocates the available server with smallest index. Delay weighted matching (DWM) [15] which maximizes the sum of the delay of scheduled packets in each time-slot. Not only throughput-optimal, but also rate-function delay-optimal maximizing the delay rate-function, rather than queue-length rate-function. The derived rate-function of DWM develops a simple threshold policy for admission control when the number of users scales linearly with the number of channels in the system. There are fixed integer delay threshold b and maximum achievable rate-function for threshold $b-1$.

However, DWM incurs a high complexity $O(n^5)$. Hybrid scheduling uses Maximum-weight matching in the first stage. Low-complexity greedy policy achieves both throughput optimality and rate-function near-optimality. D-SSG allocates servers one by one to serve a connected queue that has the largest head-of-line (HOL) delay. Greedy Frame-Based Scheduling (G-FBS) policy can exploit a key property of D-SSG. G-FBS policy guarantees a near-optimal rate-function, that D-SSG dominates G-FBS in every sample-path. D-SSG has a low complexity $2n^2+2n$. The queue-length-based scheduling Q-SSG has a positive queue-length rate-function for restricted arrival processes that not only across users, but also in time. D-SSG not only guarantees a near-optimal rate-function, but also has a

similar delay performance to the rate-function delay-optimal policy.

2.4 Achieving optimal throughput utility and low delay with CSMA algorithm by a virtual multichannel approach

Virtual-Multi-Channel CSMA (VMC-CSMA) [16] can dramatically reduce delay. Virtual-Multi-Channel CSMA (VMC-CSMA) is to use multiple virtual channels and compute a good set of feasible schedules simultaneously without switching or recomputing schedules. In contrast, CSMA algorithm has large delay that may grow exponentially with the network size, which does not fulfill the requirement of low delay in most applications. VMC-CSMA algorithm can achieve both high throughput utility and low delay with low-complexity. Both the expected packet delay and the tail distribution of the head-of-line (HOL) waiting time at each link can be bounded independently of network size.

The main novelty of the proposed algorithm to significantly reduce delay is to take advantage of multiple physical or virtual channels. Suppose that there are two separate channels for the same topology and each has half the bandwidth of the original system. If one channel uses the odd schedule, the other channel uses the even schedule. Each link can achieve both target rate of 0.5 as well as low delay. The key idea is to compute a set of good schedules for multiple channels at once rather than computing one schedule at a time and constantly switching or recomputing schedules. There is C virtual channels. Each virtual channel can have a different schedule. By randomly choosing a virtual channel and using the corresponding schedule at each time-slot, then emulate the multiple physical channels. VMC-CSMA algorithms iteratively update the schedules across all virtual channels to optimize the total system utility. VMC-CSMA only requires local information exchange and incurs a low complexity that increases linearly with the number of virtual channels C . The VMC-CSMA algorithm achieves both high throughput and low delay which does not grow with the network size with low complexity.

3. CRITICALITY AWARE SCHEDULER PRIORITIZATION IN VIRTUAL ORTHOGONAL MULTI-CHANNEL PARALLELISM (CASP-VOMCP)

This section is to describe system model, algorithm description and implementation of CASP-VOMCP, Coordinated criticality-Aware Rate-function Acceleration (CARA) as well as performance metrics of proposed CASP-VOMCP, then to derive an upper bound and lower bound on the rate-function that can be achieved by any scheduling policy. Furthermore, conduct numerical simulations and present results on throughput optimality and near-optimal rate-function for low-complexity greedy policy.

3.1 System model

Wireless system with N users is a multichannel system with only one physical channel, C virtual channels and computing multiple feasible schedules simultaneously. In each time-slot, a virtual channel can be allocated only to one user, but a user can be allocated with multiple virtual channels simultaneously. Multiple different feasible schedules group into one cluster and execute simultaneously in multiple parallelized virtual channels. It can quickly adapt to

network traffic changes. Assuming that the number of users is equal to the number of virtual channels, the admission control needs to be carefully designed if the number of users becomes too large.

Let Q_i denote FIFO queue associated with the i th user, let S_j denote j th server. Unit channel capacity, at most one packet from Q_i can be served by S_j . Let $C_{i,j}(t)$ denote the connectivity between queue Q_i and server S_j in time-slot t . $C_{i,j}(t)$ can be modeled as a Bernoulli random variable with a parameter $q \in (0,1)$,

$$C_{i,j}(t) = \begin{cases} 1, & \text{with probability } q \\ 0, & \text{with probability } 1-q. \end{cases}$$

Different application requirement employ different schedulers, different schedulers configure different weight values. The higher connectivity it has, the larger weight value the scheduler has. The larger weight values, the higher priority the scheduler has. The more criticality, the higher priority different schedulers have. Different network size determines different number of channels. In multichannel OFDM system, the key challenges are how to design efficient scheduling policy that can simultaneously achieve high throughput and low delay, high data rates, lower latency and much better user experience and how to design high-performance scheduling policies at a low complexity.

In OFDM-based LTE systems [17], the transmission time interval (TTI), within which the scheduling decisions made is only 1 ms. Assuming that a single-cell multichannel system consisting of C virtual orthogonal channels and a proportionally large number of users, with intermittent connectivity between each user and each channel. The base station maintains a separate first-in-first-out (FIFO) queue, round robin queue, WFQ queue associated with each user, which buffers the packets in the data link layer.

In VMC-CSMA policy, by randomly choosing a virtual channel and using the corresponding schedule at each time-slot, then emulate the multiple physical channels. Nevertheless, this paper proposes CASP-VOMCP which chooses multiple virtual channels in parallel access based on criticality aware scheduler priority. CASP-VOMCP only requires local information exchange and incurs a low complexity that increases linearly with the number of virtual channels C . The throughput and delay performance of CASP-VOMCP is with respect to C . Let L denote the total number of links. Moreover, under the assumption of logarithmic utility functions, the delay of each link will not grow with the network size. The delay [18] is defined as the time from packet arrival to the time when the packet is served at the MAC layer.

$\vec{V} = [V_{11}, \dots, V_{1C}]$ denotes schedule in all virtual channels, where $V_{lk} = 1$ if

link l is scheduled in the k -th virtual channel, and $\vec{V} = [\vec{V}_l]$ denote the global schedules of all virtual channels and all links. The total number of virtual channels used by link l is given by $x_l(\vec{V}) = \sum_{k=1}^C V_{lk}$. At each time-slot t , the network chooses a virtual channel $k(t)$ from 1 to C . All links in the network use the feasible schedule $\vec{S}(\vec{V})_{k(t)}$ in this time-slot, each link l transmits a packet if $V_{l,k(t)} = 1$. Each link only needs to know its own schedules $\vec{V}_l$. The long-term average rate [19] of link l is $r_l(\vec{V}) = x_l(\vec{V}) / C$, which is equal to actual transmission with probability. The average interservice time is $1 / r_l(\vec{V})$. For high throughput utility and low delay, the following optimization problem needs a solution.

$$\max_{\vec{V}} \sum_{l=1}^L U_l(r_l(\vec{V})) \quad (1)$$

3.2 Coordinated criticality-Aware Rate-function Acceleration (CARA)

CARA consists of three major components: (1) a dynamic scheduler cluster criticality predictor, (2) a greedy criticality-aware cluster scheduler, and (3) a criticality-aware virtual memory prioritization technique. **Figure 1** illustrates the different components in CARA in the context of a cognitive radio. CARA identifies lower-delay scheduler clusters that have a high likelihood to become critical cluster at each time slot t . Similarly, CARA identifies higher-throughput scheduler clusters that have a higher priority to become critical cluster. CARA identifies faster-running scheduler clusters that have a higher probability to become more critical scheduler clusters. Cluster criticality CARA allocates more

Figure 1. Different components in CARA in the Greedy Criticality-Aware Cluster Scheduler (GCACS)

power and radio resource such as channel bandwidth, memory buffer to the context of cognitive radio network predicted-to-be-critical clusters with higher scheduling priorities. To reduce critical scheduler cluster execution time by allocating more power, channel bandwidth, the number of virtual channels, memory buffer, CARA proactively reserves a certain amount of memory capacity for data flow that is useful to critical scheduler clusters. CARA ensures an optimal capacity region for the critical scheduler clusters by reducing the delay.

3.3 Critical Cluster Identification with Criticality Prediction Logic (CPL)

In addition to updating the per-cluster criticality counters based on dynamic execution progress, CPL records additional delay experienced due to shared resource contention as well as scheduler delays, while updating the criticality counter. CPL monitors the service delay time between the current and the next packet delivery for each cluster and increment the criticality counter accordingly for all clusters. **Table I** presents **Algorithm 1** the criticality counter update mechanism based on service delay time in CPL.

The per-cluster criticality counter is updated as follows:

$$nCriticality = nSchedule * w.ExeTim_{avg} + nDelay; \quad (2)$$

where $nCriticality$ represents the value of the per-cluster criticality counter, $nSchedule$ represents the relative schedule count disparity between the parallel clusters, $w.ExeTim_{avg}$ represents the per-cluster average execution time, and $nDelay$ is the delay time incurred by shared resource contention, network congestion, and the scheduler, which is the time from packet arrival to the time when the packet is served at the MAC layer.

With the critical cluster identified by CPL, GCACS is designed to give more compute resources to critical clusters by prioritizing the execution of critical clusters and by providing a larger time slot to clusters in a greedy manner. GCACS selects a ready cluster for execution based on the degree of cluster criticality determined by the per-cluster criticality counter in CPL. If there are multiple clusters have the same criticality, the cluster scheduler will select the oldest one based on the Greedy-Then-Oldest algorithm. Then GCACS greedily executes schedules from the selected critical cluster until this particular cluster has no further available schedules. Consequently, the critical cluster not only receives a higher scheduling priority but also benefits from a larger time slot.

3.4 Criticality-Aware Global Scheduler Priority (CAGSP)

In addition to allowing the critical clusters to access parallelized virtual channels more often and for longer time duration, CAGSP is designed to allocate a dynamic data flow that will be used by the critical clusters for performance guarantee. Critical clusters are delay-critical and should be treated with higher priority. Schedule Clusters with the lower delay should be assigned with higher priority. Criticality-Aware Task Scheduler (CATS) uses bottom-level longest-path priorities. CAGSP first predicts critical schedule—schedule that will be used by critical clusters—with the critical schedule predictor, and retains these critical schedule in the schedule cluster partition reserved for critical clusters.

Figure 2. Criticality Aware Scheduler Prioritization in Virtual Orthogonal Multi-Channel Parallelism (CASP-VOMCP)

Figure 2 shows the proposed CAGSP scheme and interface between the different components. Schedules partition for cluster criticality. CAGSP partitions the schedules into two parts in the granularity of ways: critical schedule clusters and non-critical schedule clusters. Dynamically tune the size of the critical and non-critical schedule cluster partitions based on the CAGSP.

Critical schedule predictor (CSP) differentiates critical schedules from non-critical schedules such that an incoming schedule will be reserved for critical or non-critical schedules. Admission control predictor (ACP) learns and predicts the number of available virtual channels and the number of feasible schedules as well as the priority, the delay of scheduler. The benefit of ACP is virtualization-based high-speed packet delivery. Virtual Orthogonal Multi-Channel Parallelism (VOMCP) constructs a memory sharing framework for network data which can achieve efficient packet processing and higher concurrency. Memory sharing framework can facilitate high speed inter-virtual channels communication. Scalable virtual channel architecture is depicted in **Figure 2**.

3.5 CASP-VOMCP Algorithm Description and Implementation

CASP-VOMCP updates the global schedule $\vec{V}$ iteratively over time, which depends on the set S of decision schedules in local schedules. Define a set S of decision schedules satisfies the following three conditions.

A1) Each decision schedule is a feasible schedule. Each link l must be scheduled by one decision schedule in S .

A2) Each decision schedule is made on criticality-aware global scheduler priority.

A3) Each link scheduled by a decision schedule can broadcast C bits to its neighbors in a time-slot.

CASP-VOMCP algorithm:

Decision Phase: Choose a decision schedule $\vec{S}^{MP}(t) = [S_l^{MP}(t)]$ at each time t .

MP denotes MaxPriority.

Update Phase: for each link l , if $S_l^{MP}(t) = 0$, let $\vec{V}_l^{MP}(t) = \vec{V}_l^{MP}(t-1)$.

Otherwise, $S_l^{MP}(t) = 1$ and $S_{l'}^{MP}(t) = 0$ for every link $l' \in \mathcal{E}_l$, perform **Algorithm 2** in **Table II**.

Scheduling Phase: A common virtual channel $k(t)$ is chosen by all links in the 5 G cellular network if $\vec{V}_{l,k(t)}^{MP}(t) = 1$ each link l transmits a packet. Perform

Algorithm 3 in **Table III**. **Table III** presents **Algorithm 3** the process of CARA with three major components.

Congestion Control: (1) Context-aware admission control: accelerate data processing and alleviate congestion. There are fixed integer delay threshold b and Maximum achievable rate-function for threshold $b-1$. (2) Throughput-based congestion control: jointly adjusted to control throughput on incast congestion. (3) Rate-based congestion control: decrease packets sending rate by half. (4) Distribution-based congestion control [15]: each link l injects a random number of packets according to a Poisson distribution with mean

$$r_l = \arg \max_{r \geq 0} \{U_l(r) - \beta Q_l(t)r\} \text{ where } \beta > 0. \quad (3)$$

These prioritization schedulers are performed dynamically and potentially in parallel in different virtual channels simultaneously. While some schedulers are being prioritized, others assigned to available virtual channels to execute. **Figure 3** shows a scheme of the operation of the Criticality-Aware Global Scheduler Priority (CAGSP). The number inside each node is the bottom level of the schedule: the length of the longest path from this node to node with rank 0. The priority of a schedule is given by its bottom level. The number outside each node is the schedule id which is used in the text to refer to each schedule. Critical schedules

Figure 3. Round Robin Schedule prioritization with CATS. Nodes are marked with the bottom level of each scheduler. Pattern-purple nodes mark the critical schedulers with highest priority which processed in low delay queue. The blue nodes and orange nodes mark non-critical schedulers with low priority.

are inserted in the critical queue, and non-critical schedules to the non-critical queue. The insertion is ordered with the highest priorities at the head of the queue and the lowest priorities at the tail.

Clustering schedules first separate schedules into clusters, where each cluster is to be executed on the different queues. During the clustering stage, assume an unlimited number of available queues. If the number of clusters exceeds the size of memory space, merging stage joins multiple clusters or sharing memory framework so that they can match the requirement of memory space. The heuristic clusters schedules that can execute in parallel according to their connectivity $C(i, j)$ between queue Q_i and server S_j and assigns priorities to the schedules in a cluster according to its execution time, schedules with the highest execution time have the highest priority. The scheduler enables dynamic scheduling of multiple-sized schedules for heterogeneous systems. CASP-VOMCP allows multiple implementations of a given schedule to be executed on different virtual channels. The scheduler assigns the execution of a schedule to the best resource according to its earliest finish time.

Scheduling heuristics focus on the critical schedules to reduce total execution time [20]. To identify the schedules in the critical clusters, the rank of schedule is the maximum sum of computation and communication cost of the schedules from the packet arrive to packet is serviced. Schedule queue maintains a list of schedules sorted in decreasing order of their rank. CASP-VOMCP assigns the schedule with the highest rank to the cluster that finishes the execution of schedule at the earliest time. The schedule with the highest rank belongs to the critical cluster. It dynamically updates the computation and communication costs on multiple schedules of multiple clusters. On each step, these schedules are dynamically assigned to the clusters that minimize the execution time of critical cluster. When a decision schedule becomes ready, all critical schedules finished their execution, it is assigned to a ready queue [21]. The schedule is inserted in the corresponding ready queue: schedules in the critical cluster ready queue will be executed firstly, and tasks in the non-critical cluster queue will be executed later. When a cluster becomes idle, it tries to retrieve a schedule from its corresponding ready queue to execute.

Each cluster has a list to include its finished schedules (plist) [22]. The priority given to a schedule is the bottom level of the schedule. **Table IV Algorithm 4** shows the schedule prioritization. Using plist for each schedule, update the priority on each ready schedule and finished schedule. If the plist of the current task (currPred) is empty, all the ready schedules have finished execution. If the priority of the current schedule (currPred) remains unchanged, which means that successor schedule (succ) does not belong to the longest path because its predecessor already has a higher priority (bottom level). The longest path starts from the schedule with maximum bottom level. At runtime, the longest path changes as schedules complete execution and new schedule are created. CAGSP manages to detect changes and dynamically decide if the ready schedule belongs to the longest path.

To determine the criticality of a schedule [23], CAGSP keeps track of last discovered critical schedule. Then for each schedule that becomes ready, CAGSP checks the following conditions: (1) whether the priority of the current ready schedule is higher than the priority of the last discovered critical schedule (maxPriority). (2) Whether the current ready schedule is the highest-priority immediate successor of the last discovered critical schedule.

Scheduler can be marked as critical schedules with priority higher or equal to the priority of the last critical schedule. **Table V** shows **Algorithm 5** Criticality Aware Scheduler Prioritization algorithm. The variable maxPriority is used to store the priority of the last critical schedule, and maxPrioritySchedule is used to store the last critical schedule. Initially, maxPriority is set to 1 and maxPrioritySchedule is set to NULL. On the first ready schedule, if its priority is higher or equal than 1, it is considered to be the first schedule of the longest path. It is inserted in the critical queue and the variables maxPriority and maxPrioritySchedule are updated accordingly to determine correctly the criticality of the next ready schedule. In the rest of cases the schedule is not considered critical and it is inserted in the non-critical queue. If the priority of the ready schedule is equal to maxPriority – 1, and if it belongs to the successors of the schedule with the maximum priority and to the longest path, the schedule is determined to be critical, it is inserted in the critical cluster queue and the variables maxPriority and maxPrioritySchedule are updated.

Figure 4 depicts how to execute CAGSP. The hollow nodes are schedules that have finished execution and purple nodes are critical schedules. The number insider the nodes indicate their priority and the number outside the nodes show the schedule id, which is assigned in schedule creation order. The variable maxPriority corresponds to the priority of the last critical schedule and the maxScheduleSucc is the list of the successors the last Schedule, filled with the schedule ids of the successors. Initially, max-Priority is set to 1 and maxScheduleSucc is empty. When schedule 2 is about to be ready, it is inserted in the critical queue because its priority is higher than the maximum, which at the beginning is 1. Then, the value of maxPriority is set to 6 (priority of schedule 2), and the maxScheduleSucc list is updated with the successors of schedule. At the point where the entire hollow schedules have finished execution, the values of maxPriority and maxScheduleSucc are updated as shown in **Figure 4**. For every newly-ready schedule, the conditions listed before will be evaluated. When schedule 8 is ready, it will not be considered as critical because it does not belong to the maxScheduleSucc list and its priority is not equal to max purple – 1.

Table I

Algorithm 1 The criticality counter with service delay
1: function ClusterScheduler
➔ select a ready cluster to execute
2: while IdleAllClusters do

Figure 4. CAGSP execution. $\{1,2,3,4,5,6\}$ hollow nodes indicate finished schedules and pattern-purple nodes indicate critical schedules will be ready for execution with highest priority.

```

➔ select clusters in the order based on the scheduling policy
3:  $w \leftarrow \text{findNextCluster}(1,2,3,\dots,N-1)$ 
4: if  $w.\text{isRready}()$ 
    then Delay time = total delay time between two consecutive packets
5:  $w.n\text{Delay} \leftarrow w.n\text{Delay} + \text{Delay time}$  ( $n=1,2,\dots,C$ )
6: SchedulerExecute( $w$ )
7: end if
8: end while
9: end function

```

Table II

Algorithm 2 Update phase for link if $S_l^D(t) = 1$

```

1: Choose a permutation  $(n_1^l, n_2^l, \dots, n_C^l)$  of the set  $\{1,2,\dots,C\}$  according to
   criticality counter in Algorithm 1.
2: Let  $f_l(x) = \exp(\alpha U_l(\frac{x}{C}))$  and  $x_l^1(x) = \sum_{k=1}^C V_{lk}(t-1)$ 
3: for  $i=1$  to  $C$  do
4: if  $V_{l',n_i^l}(t-1) = 1$  for any link  $l' \in \mathcal{E}_l$  then
5:  $V_{l,n_i^l}(t) = V_{l,n_i^l}(t-1)$ 
6: else

```

7: $V_{l,n_l}(t)$ is determined with CASP using Algorithm 5.

8: **end if**

9: $x_l^{i+1} = x_l^i + V_{l,n_l}(t) - V_{l,n_l}(t-1)$

10: **end for**

11: Link l broadcasts $\vec{V}_l(t)$ to all of its neighbors.

Table III

Algorithm 3 The Coordinated criticality-Aware Rate-function Acceleration algorithm (CARA)

1: **Function** AdmissionControlPredictor (rate, delay, throughput)
Select partition and compute maximum rate function by formula (29), minimum rate function by formula (33) and average rate of link l is $r_l(\vec{V}) = x_l(\vec{V}) / C$

2: Criticality-Aware Global Scheduler Priority return delay threshold.

3: VirtualChannel.delay $\leftarrow$ (VirtualChannelID, maximum rate function)

4: **If** ACP[VirtualChannel.delay] > Threshold **then**

5: Predicted to be critical schedule

6: CriticalSchedule.execution(channel ID)

7: set ACP access channel ID

8: **else** predicted to be non-critical cluster schedule

9: NonCriticalSchedule.access(channelID)

10: set ACP access channel ID

11: **end if**

12: **end function**

13: **Function** DynamicSchedulerClusterCriticalityPredictor (cluster ID, channel ID, maxpriority)

// Critical Cluster Identification with Criticality Prediction Logic (CPL)

Critical Schedule Prediction using Algorithm 4

14: **If** IsCriticalCluster(chan.ClusterID) **then**

15: correct prediction; increment ACP

16: ACP[VirtualChannel.delay]++

```

17: CSP[VirtualChannel.delay]++
18: else
19:   schedule execution from non-critical cluster
20:   CSP[VirtualChannel.delay]++
21: end if
22: end function
23: Function GreedyCriticality-AwareClusterScheduler (cluster ID, channel
ID, maxpriority) //Greedy Criticality-Aware Cluster Scheduler(GCACS)
24: if (Criticality[i]== Criticality [i-1])
25:   search oldest cluster schedule i-1
26:   //Greedy-Then-Oldest algorithm
27:   maxpriority= priorityOf(i-1);
28:   maxPrioritySchedule=i-1;
29: end if
30: end function
31: Function Criticality-AwareVirtualMemoryPrioritization (cluster ID,
channel ID, maxpriority)
32: //Criticality-Aware Global Scheduler Priority (CAGSP)
33: if (CSP.V==false) And
(CriticalSchedule.execution(channelID)==CriticalSchedule)
Then incorrect prediction, schedule should be assigned to non-critical
cluster;decrement ACP
34: ACP[VirtualChannel.delay]++
35: else if ((CSP.V==false) And
(CriticalSchedule.execution(channelID)==NonCriticalSchedule)
36: then CSP[VirtualChannel.delay]++
37: end if
38: end function

```

Table IV

Algorithm 4 Critical Cluster Identification with Criticality Prediction Logic (CPL)

```

1: void prioritize_schedule (schedule * succ) {
2:   int purple = succ → priority;
3:   list plist = plistOf (succ);
4:   schedule * currPred;
5:   while (not isEmpty (plist)) {
6:     currPred = plist.next( );
7:     if (priorityOf(currPred) < purple + 1) {
8:       currPred → priority = purple + 1;
9:       if (isReady(currPred))
10:         readyQueueOf(currPred)→reorder();
11:       prioritize_schedule(currPred);
12:   }
13: else return;
14: }
15: }

```

Table V

Algorithm 5 The Criticality Aware Scheduler Prioritization (CASP)
algorithm implementation

```

1: int maxPriority = 1;
2: schedule *maxPrioritySchedule = NULL;
3: void execute_schedule(schedule * t) {
4:   if ( t → priority >= maxPriority )
5:     { // schedule is critical
6:       critical_queue.push(t);
7:       maxPriority = priorityOf(t);
8:       maxPrioritySchedule = t;
9:       return;
10:    } // schedule is non-critical
11:   non_critical_queue.push(t);
12: }

```

4. PERFORMANCE MEASUREMENT

Consider three performance metrics: 1) the throughput 2) the steady-state probability that the largest packet delay in the system exceeds a certain fixed threshold b , and 3) its rate-function in many-channel many-user regime.

Optimal throughput region [15] is defined as the union of the throughput regions of all possible scheduling policies, which is denoted by Λ^* . A scheduling policy is throughput-optimal if it can stabilize any arrival rate vector inside Λ^* . Achieve throughput-optimality in multichannel systems, each server choose a connected queue with a large enough weight (queue length or delay). The expected packet delay at link l must be equal to $1/R_l$, which is upper-bounded by

$\frac{1}{(1-\varepsilon)r_l^{\min}}$. A high throughput at link l refers to a low expected packet delay

$$P\{d_l(t) \geq d\} \leq (1-r_l^{\min})^d + \varepsilon \quad (4)$$

where $d_l(t)$ is HOL waiting time.

$$\text{Assume } 0 < h < \frac{1}{(\Delta+2)(K-1)} \text{ and } \frac{\Delta_l+1}{C} < \frac{1}{K_l(\Delta_l+2)} - \frac{h(K_l-1)}{K_l}, \forall l,$$

under CASP-VOMCP algorithm,

$$r_l^{\min} \geq \frac{1}{K_l(\Delta_l+2)} - \frac{h(K_l-1)}{K_l} - \frac{\Delta_l+1}{C}.$$

If $0 < h < \frac{1}{2(\Delta+2)(K-1)}$ and $C \geq 4K(\Delta+1)(\Delta+2)$, then $r_l^{\min} \geq \frac{1}{4K(\Delta+2)}$.

$\Delta_l = |\varepsilon_l|$ is the number of links in the neighborhood of link l . K_l is the maximum number of links that can be scheduled simultaneously in the neighborhood of link l .

When single-slot reconfiguration delay T_r , there is a frame length function

$$x_k = T_r + \left(\sum_i Q_i(t_k)\right)^a \quad (5)$$

for a fixed $a \in (0,1)$, where t_k is the first slot of the k th frame, $Q(t_k)$ is the queue lengths at t_k .

Assuming that the system is stationary and ergodic, let $W(0) = \max_{1 \leq i \leq n} W_i(0)$ denote the largest HOL delay over all the queues (i.e., the largest packet delay in the system) in the steady state, then define rate-function

$I(b)$ as the delay-rate of the probability that $W(0)$ exceeds any fixed integer threshold $b \geq 0$, as the system size n goes to infinity, i.e.,

$$I(b) = \lim_{n \rightarrow \infty} \frac{-1}{n} \log_2 P(W(0) > b). \quad (6)$$

The estimate the delay-violation probability using $P(W(0) > b) = \exp(-nI(b))$ based on the knowledge of rate-function. With a large n , a larger value of the rate-function implies a better delay performance, that is, a smaller probability that the largest packet delay exceeds a certain threshold. Optimal rate-function is defined as the maximum achievable rate-function over all possible schedulers, which is denoted by $I^*(b)$. A scheduler is rate-function delay-optimal if it achieves the optimal rate-function $I^*(b)$ for any fixed integer threshold $b \geq 0$.

4.1 Upper bound on the rate-function

Let $A_i(t)$ denote the number of packet arrivals to queue Q_i in time slot t . Let

$$A(t_1, t_2) = \sum_{\tau=t_1}^{t_2} A_i(\tau)$$

denote the cumulative arrivals to the system from time t_1 to

time t_2 . Let λ_i denote the mean arrival rate to queue Q_i in time slot t . let

$\lambda = [\lambda_1, \lambda_2, \dots, \lambda_n]$ denote the arrival rate vector. Let $I_{AG}(t, x)$ denote the asymptotic decay-rate of the probability that in any interval of t time-slots, the total number of arrivals is greater than $n(t+x)$, as n tends to infinity, i.e.,

$$I_{AG}(t, x) = \liminf_{n \rightarrow \infty} \frac{-1}{n} \log_2 P(A(-t+1, 0) > n(t+x)) \quad (7)$$

Let $I_{AG}(x)$ be the infimum of $I_{AG}(t, x)$ over all $t > 0$, that is

$$I_{AG}(x) = \inf_{t > 0} I_{AG}(t, x). \quad (8)$$

Define $I_x = \log_2\left(\frac{1}{1-q}\right)$, for any scheduling algorithm, upper bound of rate-

function can be computed as follows:

$$\limsup_{n \rightarrow \infty} \frac{-1}{n} \log_2 P(W(0) > b) \quad (9)$$

$$\leq \min\{(b+1)I_x, \min_{0 \leq c \leq b} \{I_{AG}(b-c) + cI_x\}\} \quad (10)$$

$$=I_U(b).$$

$(b+1)I_x$: the event that a queue with at least one packet is disconnected from all of the n servers for consecutive $b+1$ time-slots. $I_{AG}(b-c)$: the event that the arrivals are too bursty during the interval of $[-t-b, -b-1]$ such that at the beginning of time-slot c for $c \leq b$, there exists at least one packet remaining in the queue $Q1$. cI_x : the event that the services are sluggish such that queue $Q1$ is disconnected from all of the n servers for the following consecutive c time-slots. Both of the above events will lead to the delay-violation event $W(0) > b$ under all the scheduling policies. $I_U(b)$ is an upper bound on the rate-function that can be achieved by any scheduling policy. For the optimal rate-function $I^*(b)$, $I^*(b) \leq I_U(b)$ for any fixed integer threshold $b \geq 0$. Optimal rate-function is $I^*(b) = (b+1) \log_2 \left(\frac{1}{1-q} \right)$.

4.2 Lower bound on the rate-function

Lemma 1: For any scheduling algorithm, lower bound of rate-function can be computed as follows:

$$I_L(b) = \lim_{n \rightarrow \infty} \inf \frac{-1}{n} \log_2 P(W(0) > b) \geq I^*(b-1) \quad (12)$$

$I^*(b-1)$: Optimal rate-function for threshold $b-1$.

$$I(b) \geq I_U(b-1) \geq I^*(b-1), \quad (13)$$

$$I(b) \geq (b/(b+1)) I^*(b), \quad (14)$$

where $I^*(b) = (b+1) \log_2 \left(\frac{1}{1-q} \right)$.

$$I_L(b) = b \log_2 \left(\frac{1}{1-q} \right). \quad (15)$$

4.3 Utility Optimality

This section discusses the capacity/utility performance in VMC-VOMCP algorithm.

The number of virtual channel $C > \frac{2 \log_2 L}{3\varepsilon^2}$ for any $\varepsilon \leq 0.1$ and L links.

Global schedule $\vec{V}(t)$ as a Markov chain, $r_l(\vec{V}^s) \geq R_l^* - \varepsilon$, for all link l .

$$U(\vec{r}) = \sum_{l=1}^L U_l(r_l) \quad (16)$$

$$P\{U(\vec{r}(\vec{V}(t))) \geq \sum_{l=1}^L U_l([R_l^* - \varepsilon]^+)\} \geq 1 - \varepsilon \quad (17)$$

where R_l^* is the optimal solution of problem (1).

The time-averaged throughput R_l of link l has a lower bound

$$R_l \geq (1 - \varepsilon) r_l^{\min} \cdot U(\vec{R}) \geq (1 - \varepsilon) U([R_l^* - \varepsilon]^+), \quad \text{where}$$

$$r_l^{\min} = \min_{\{\vec{V} \in \mathcal{V} | U(\vec{r}(\vec{V})) = U(\vec{r}(\vec{V}^{\max}))\}} r_l(\vec{V}) \text{ denotes as the worst rate for link } l \text{ among all}$$

global schedules with the maximum utility.

5. SIMULATION RESULTS

Construct 23 wireless nodes deployed in a $900 \times 900 m^2$ 5G cellular network.

The transmission range and interference range of each node is set to 900 m and 90m, respectively. Thus, $K=10$. Peak data rate is 10 Gbps, minimal data rate is 100 Mbps. Latency is less than 1 ms. 5G adopted full duplex cognitive radio transmitting signal at 60 GHz. Source node has 20 packets transmitted. Simulations for such 5 G cellular network system are with n servers and n users,

where $n \in \{10, 20, \dots, 100\}$. The simulation period lasts for 10^9 time-slots for each

policy. For channel model, assume ON-OFF channels with unit capacity, set $q=0.75$. Run simulations in a Mac PC with Intel Core T5470 1.6 GHz CPU and

1GB memory. The weight is chosen as $w_l(t) = \log_2(0.5 Q_l(t))$. For CASP-

VOCMP, let $C=30$, $\varepsilon = 0.3$.

5.1 Performance comparison of different scheduling policies with virtual channels

Fig.5 compares the performance of different scheduling policies in the case with virtual channels for delay threshold $b=8$. It demonstrates the probabilities that the largest HOL delay exceeds the threshold b under VFMW, FBDC and CASP-VOMCP scheduling schemes. VFMW has lower probability of delay than FBDC policy because of Max-Weight policy with adaptive frame sizes in VFMW scheme. As the number of secondary user increment considerably, the probability of delay becomes smaller. It has been shown that CASP-VOMCP empirically achieves near-optimal delay performance.

Fig. 6 plots the performance comparison of different scheduling policies in the case with virtual channels for 23 secondary users. It demonstrates the probabilities that the largest HOL delay exceeds the threshold b under D-SSG,

VMC-CSMA and CASP-VOMCP scheduling schemes. VMC-CSMA has higher delay probability than D-SSG and CASP-VOMCP. CASP-VOMCP demonstrates the probability for different delay thresholds b to investigate the performance of good policy for fixed users n .

5.2 Performance evaluation of CASP-VOMP policy

Fig. 7 shows the total utility of different delay parameter values under different virtual channels under CASP-VOMCP policies. Compared with the decrement of delay parameter a when it equals to 16, total utility achieves an ideal performance. As delay parameter is 64, there is a minimal utility performance. When the rate function is optimal, it can obtain the higher total utility. When the rate function is upper bound, total utility is larger than that of lower bound. When a is larger, the utility value after convergence is closer to the optimal value. Larger a incurs

longer convergence time. $r_l = \frac{x_l^i}{C}$, as C increases, to maintain the same probability

of adding another virtual channel, increase a proportional to C .

Fig. 8 indicates the utility function of sum throughput under different reconfigurable delays with average queue length $Q_i=10$ under CASP-VOMP policy. As the increment of reconfigurable delay, the sum throughput augments accordingly. When reconfigurable delay equals to 60s, it provides a good throughput-delay performance in CASP-VOMP policy. The larger number of virtual channels there are, the higher sum throughput it has.

Fig.9 illustrates the utility function of sum throughput under different average queue lengths with the change of reconfigurable delay. Due to the soaring of total average queue sizes, the sum-throughput grows up significantly. When reconfigurable delay augments, CASP-VOMP can achieve the optimal sum throughput.

Fig.10 presents the execution time of critical and non-critical clusters with various priorities in different virtual channels. Compared with (a) (b), it indicates that high priority schedule has smaller execution time than lower priority schedule. Meantime, it shows that critical cluster schedules run faster than non-critical clusters compared with (b) (c).

Fig.11 depicts the execution time of different virtual channels with different priorities. High priority schedule within higher delay queue runs faster than Low priority schedules compared with (b) (c). Low priority schedules wait in higher delay queue which require more execution time. High priority schedule within higher delay queue executes quickly than that of lower delay queue compared with (a) (b).

Fig.5 Delay probability of different scheduling polices with different number of secondary users for delay threshold $b=8$.

Fig.6 Delay probability of different scheduling polices with different delay thresholds for 23 secondary users.

Fig.7 Total utility of different delay parameter values under different virtual channels in CASP-VOMCP policy.

Fig.8 Utility function of sum throughput under different reconfigurable delays with average queue length $Q_i=10$.

Fig.9 Utility function of sum throughput under different average queue lengths with the change of reconfigurable delay

Fig.12 compares that the execution time with different priority schedules in critical cluster and non-critical cluster. When high priority schedule in non-critical cluster occupies 8 to 18 virtual channels, it can run the same speed among the critical cluster and non-critical cluster, high priority schedule and low priority.

Fig.13 elaborates that criticality with different priority schedules in critical cluster and non-critical cluster. High priority schedule in critical cluster has highest criticality. As the number of virtual channels soars up, the criticality plumps correspondingly. Low priority schedule in critical cluster runs faster than high priority schedule in non-critical cluster.

Fig.14 indicates that the execution time of different priority schedules within critical cluster and non-critical cluster over virtual channels. High priority schedule within critical cluster requires longer execution time than low priority schedule within critical cluster compares with (a) (c). Non-critical cluster schedules need smaller execution time than critical cluster schedules compared with (a) (b).

Fig. 15 demonstrates that criticality of critical cluster and non-critical cluster's scheduling priority over virtual channels. High priority schedule within

critical cluster has larger criticality than low priority schedule within critical cluster compared with (a) (c). Critical cluster schedules can achieve more optimal criticality performance than non-critical cluster schedules compared with (a) (b).

Fig. 16 shows that criticality prediction accuracy of CARA with CSP and ACP at maximum rate, average rate function and minimum rate function. In light of the increment of reconfigurable delay, criticality prediction accuracy approaches optimal. When CSP implements with maximum rate, criticality prediction accuracy is the highest. The criticality prediction accuracy of CSP is better than that of ACP. The higher speed it executes, the more accuracy the predictor has.

Fig. 17 presents that execution time improvement of CARA with CSP and ACP at maximum rate, average rate function, and minimum rate function. CSP and ACP have a similar distribution in execution time. ACP at maximum rate requires highest execution time than that of average rate function and minimum rate function. CSP runs faster than ASP at minimum rate function.

Fig. 18 elaborates that the throughput improvement of $CARA_{CPL}$, $CARA_{GCACS}$, $CARA_{CAGSP}$. As the HOL wait time augments, the throughput improvement of CARA soars up considerable. GCACS can enhance more throughput performance than CPL. CAGSP improves slightly than CPL and GCACS in sum throughput.

Fig. 19 depicts that the HOL waiting time of $CARA_{CPL}$, $CARA_{GCACS}$, $CARA_{CAGSP}$. As delay threshold increases, CARA requires more HOL wait time. CAGSP has largest wait time than GCACS and CPL. CPL has lowest HOL wait time than others.

Fig. 20 compares that the execution time improvement of $CARA_{CPL}$, $CARA_{GCACS}$, $CARA_{CAGSP}$. In light of the increment of the number of virtual channels, for a fixed value of threshold b to compare the execution time enhancement of CARA, execution time improvement of CARA grows up. Compared with GCACS and CPL, CAGSP has largest performance optimization which has more superiority in CASP-VOMCP policy.

Fig.10 Comparison of execution time of clusters in different virtual channels

Fig.11 Comparison of execution time of different virtual channels

Fig.12 Comparison of execution time with different priority

schedules in critical cluster and non-critical cluster

Fig.13 Comparison of criticality with different priority schedules in critical cluster and non-critical cluster

Fig.14 Execution time of different priority schedules within critical cluster and non-critical cluster over virtual channels.

Fig.18 The throughput improvement of $CARA_{CPL}$, $CARA_{GCACS}$, $CARA_{CAGSP}$

Fig.19 The HOL waiting time of $CARA_{CPL}$, $CARA_{GCACS}$, $CARA_{CAGSP}$

Fig.20 The execution time improvement of $CARA_{CPL}$, $CARA_{GCACS}$, $CARA_{CAGSP}$

6. CONCLUSION

This paper summarizes the current state-of-art technical solutions for 5 G communication. The most significant contribution is to develop system model, algorithm implementation of CASP-VOMCP, CARA as well as performance metrics of proposed CASP-VOMCP, then to derive a lower bound on the rate-function that can be achieved by any scheduling policy. Furthermore, conduct numerical simulations and present results on throughput optimality and near-optimal rate-function for low-complexity greedy policy.

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