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Massive MIMO Pilot Scheduling over Cloud RAN for Industry 4.0

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Abstract—**Cloud-RAN (C-RAN) is a promising paradigm for the next generation radio access network infrastructure, which offers centralized and coordinated base-band signal processing in a BBU pool. This requires extremely low latency fronthaul links to achieve real-time signal processing. In this paper, we investigate massive MIMO pilot scheduling in a C-RAN infrastructure under a factory automation scenario. We use simulations to provide insights on the feasibility of C-RAN deployment for industrial communication, which has stringent criteria to meet Industry 4.0 standards. Our experiment results show that, concerning a pilot scheduling problem, the C-RAN system is capable of meeting the industrial criteria when there is fronthaul latency in the order of milliseconds.**

Index Terms—**Cloud-RAN, Massive MIMO, Latency Constraint fronthaul, MAC scheduling, Industry 4.0**

I. INTRODUCTION

In the context of Industry 4.0 and Internet of Things (IoT), the communication networks are expected to evolve towards wireless communication, which should have characteristics of high reliability, high capacity, large throughput and low latency to meet the performance requirements of different industrial applications. The Fifth Generation Wireless Specifications (5G) promises to provide these characteristics and thus is envisioned to be one of the future infrastructures for industrial communication networks. Cloud-RAN (C-RAN) is an intriguing candidate Radio Access Network (RAN) architecture for 5G that enables softwarization and resource centralization in radio access networks and promises to provide mobile Internet access with low cost and highly efficient network operations.

The basic concept of C-RAN is to detach the Base-Band processing Unit (BBU) from multiple legacy radio base stations and centralize them into a BBU pool. The remaining Remote Radio Heads (RRH) are only equipped with basic radio-frequency functionalities like transmitting, receiving and analog/digital conversion. The BBU pool allows for base-band signal processing in a cooperative way for multiple RRH sites.

However, as of now various challenges remain to be solved in order to deploy the C-RAN infrastructure for the next generation mobile networks as explained in [1], [2]. One important challenge is to establish the fronthaul links that enable communication between the BBU pool and RRHs. These fronthaul links must comply with the stringent bandwidth and latency requirements for C-RAN.

Massive Multiple Input Multiple Output (MIMO) is another essential enabler for the next generation RAN that significantly increases the system capacity in order to handle the rapid growth of traffic in mobile networks. However, these large scale antenna systems require a huge amount of computational power for base-band signal processing. Therefore, it would be beneficial to adopt massive MIMO in C-RAN and to split part of the processing functionalities to a remote BBU pool. However, offloading the computational resources of such large antenna systems to a remote BBU pool implies that they may suffer from latency limitations while transmitting enormous amount of data to the computational unit. [3].

C-RAN systems build on cloud-native technologies, which also leads to problems for real-time processing, since the virtualization technology introduces more layers on the data path along the processing chain. These characteristics of the C-RAN system cause long-tailed delay and jitter in the RRH-BBU communication. This could also introduce catastrophic interruptions in the real-time signal processing [4].

In order to deploy C-RAN infrastructure with massive MIMO for industrial automation networks and meet the stringent performance requirements, we must show that the latency in the system does not collapse the network function performance and that the impact of the delay can be mitigated with simple strategies. This system is only viable if the massive MIMO signal processing chain can guarantee that the performance in terms of communication reliability and connectivity still meet the industrial criteria when the data transmission between two functions are delayed.

As both massive MIMO and C-RAN are the most competitive candidates for building up the infrastructure of future mobile radio access networks, investigations on the combination of the two techniques have received a lot of interest. In [5], [6], the functionality split in massive MIMO RRH C-RAN system is addressed to tackle the bandwidth fronthaul limitation. Instead of offloading the whole base-band function chain to the BBU, the authors keep part of the function blocks in the RRH and allow them to be processed locally.Other solutions to the limited-fronthaul in massive MIMO C-RAN system are investigated as well. A prefiltering C-RAN architecture is proposed in [7] to compress the link data rate over the fronthaul and to keep the RRH structure as thin as possible. In [8], pilot contamination and imperfect channel estimation are considered as the impacts of the limited fronthaul. In [9], the authors proposed a decision-theoretic framework to tackle the delayed Channel State Information (CSI) for a rate

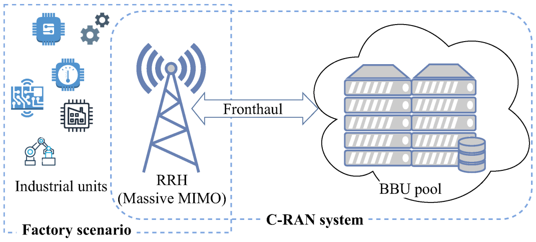

Fig. 1: Target system architecture

allocation problem in C-RAN and optimize the end-to-end TCP throughput performance for the mobile edge cloud users. In their formulation, the TCP response latency experienced by the users is considered as a constraint and only a low mobility scenario is addressed.

To the best of our knowledge, with regard to the research on massive MIMO with C-RAN, the pilot scheduling problem has not yet been addressed. Likewise, few have considered the latency as the main constraint in the fronthaul in their problem formulation, however latency significantly affects both scheduling performance and user experience.

In this paper, we target a C-RAN system, which introduces delays to the single processing chain due to the latency constraint fronthaul and cloud environment. In that context, we address the pilot scheduling function at the Medium Access Control Layer (MAC) layer of massive MIMO that is implemented in the BBU pool of the addressed C-RAN system. We focus on the feasibility of deploying such a system under industrial automation requirements from the perspective of the scheduling performance, which is affected by several factors of the system. To address the challenge, we applied a commonly used Earlist Deadline First (EDF) strategy on the pilot scheduling problem to evaluate a latency constrained system using simulations. Our investigations show that C-RAN is capable of providing a reliable communication infrastructure that meets the criteria for industrial automation.

II. TARGETED SYSTEM

In this paper, we target a C-RAN architecture that includes one BBU pool and one massive MIMO RRH, connected with a fronthaul link, shown in Fig. 1. As the MAC layer scheduling function is the main focus of our problem, we assume that the Physical Layer (PHY) functionalities are operated on the RRH and no raw base-band data blocks are transmitted over the fronthaul link. Thus we neglect the bandwidth limitation.

A. C-RAN System

In C-RAN, the traditional distributed base-band processing units (BBUs) are detached from the radio-frequency processing units (RRHs) and are centralized into a BBU pool. The remaining RRHs are co-located with the antenna while the BBU pool is responsible for the base-band processing of multiple RRHs. The BBU pool is connected to the target RRHs by fronthaul links. For a manufacturing process, the communication distance is normally less than 100m [10], thus we assume that all the units can be covered by the radio range of one RRH in our target scenario.

The fronthaul link between the RRH and the BBU pool could be up to 40km long [11]. Due to this geographic separation and the cloud environment in the BBU pool, the C-RAN architecture inevitability incurs delay between network functions and essentially breaks down the signal processing chain of an access network. The permissible round-trip delay of the fronthaul link varies from 5µs to 400µs depending on different techniques and function splits [12]. However, in Section IV-1 we show that the round-trip delay in our target system could be up to milliseconds, which imposes more interruptions in the processing chain.

B. Massive MIMO and Radio Resources

We use massive MIMO as the RRH of our target system. The time-frequency space of a single massive MIMO system can be divided into coherence blocks, which is the largest time interval during which the channel can be viewed as time-invariant and where channel frequency response is approximately constant for an end-user. A coherence block is shared by uplink data, downlink data and uplink pilot transmissions. The uplink pilots are used by the base station to estimate each end-user's CSI, which is needed for precoding to process the input and output data [13]. Thus, in every coherence interval, a new pilot is needed for a given end-user to transmit data successfully. In this paper, we consider the uplink pilots as the resources required by the end-users in an industrial automation scenario before a transmission can start.

The length of a coherence interval mostly depends on the end-users' mobility when the carrier frequency is fixed [13]. An end-user with lower moving velocity yields a longer interval, therefore it requires fewer pilots to transmit the same amount of data compared to one with higher mobility.

C. Industrial Communication Network

We address an indoor industrial automation scenario, where there are numerous sensors, controllers and actuators, here called Critical Units (CU), which are part of a dynamic control system and are interconnected by a wireless industrial network. The traffic generated by the control operations with these units has key requirements such as less than 10ms latency, availability within the range of 95%-99.999% and density of 10000 devices per km^2, but the mobility of these units are mostly fixed or very low, since there is usually an indoor environment for industrial automation [14].

Because of the processes' low latency requirement, in this paper we assume that each transmission request has a hard deadline. If a unit has not been assigned a channel resource within the deadline, the transmission attempt failed and the data is discarded. Also, as most units have low mobility in the scenario, the coherence interval in the massive MIMO time-frequency space can be relatively long, and thus, a larger number of units can be served by the radio system simultaneously.

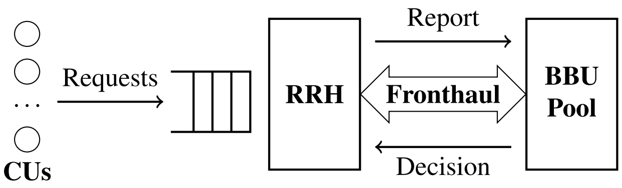

Fig. 2: Simulation model

To complicate things, there are many types of units in such a system, some with less stringent requirements and thus, the priority of such units is lower than the CUs. The traffic generated by these units is considered as background traffic in the system. Therefore, it is important to optimize the radio resources allocated to the prioritized traffic from CUs, since the remaining resources can be allocated to the low-priority background traffic.

D. Pilots Scheduling Strategy

In our targeted industrial setting, the requests from CUs have strict deadlines but the number of pilots in a coherence interval is limited. In order that the CUs get assigned the pilots for data transmissions within their deadlines, we need to deploy a MAC scheduler to allocate the pilots. In our targeted C-RAN system, the scheduler is located in the BBU pool. The objective of the scheduler is to serve as many requests as possible within their deadlines. The background traffic will be served if there are pilots left in each coherence interval after the requests from CUs have been scheduled.

When allocating pilots to the CUs, the massive MIMO RRH follows the decisions made by the remote scheduler to allocate the pilots to the CUs. In order to investigate the feasibility of C-RAN deployment for industrial automation scenarios, we applied a scheduling strategy with EDF policy on the MAC layer to allocate the pilots to the CUs. The EDF policy guarantees that the CUs whose requests have earliest deadlines get the pilots first.

We propose the two following performance metrics for investigating how massive MIMO pilot scheduling is affected by the C-RAN constraints.

Loss (L): A request is dropped if it is not scheduled within its deadline. The loss can be calculated as the ratio between the dropped transmissions and the total number of requests.

Pilot utilization (U): A pilot is wasted every time it is allocated to a CU that has nothing to send. The utilization of pilots can be calculated as the ratio between the pilots that are successfully assigned for transmission requests and the total number of pilots that are allocated.

III. SIMULATION MODEL

In this section, we present the system simulation model shown in Fig.2, given that in total K active CUs are covered by the radio range of the RRH. The RRH communicates with the BBU pool via the fronthaul link in order to allocate pilots to the CUs.

A. RRH and BBU Pool Model

We consider that each CU only needs one pilot for the base station to estimate its channel state information in order to serve the transmission requests in a coherence interval. We assume that the number of available pilots in an interval is proportional to the length of the interval, which is determined by the mobility of the CUs. Since the end-users can be multiplexed in the spatial domain in massive MIMO, if a given CU gets assigned a pilot, we consider that the number of its requests that can be served is also proportional to the interval length.

We denote the minimum interval length of our system as T_c, during which p pilots are available, implying that maximum p CUs can be assigned the pilots during T_c and one transmission request from each CU is served if it is assigned a pilot. We also denote by T_{slot} the actual length of a coherence interval, as well as as an allocation time slot in our scheduling problem, and there are P pilots available during each slot. When $T_{slot} = T_c$, we call it a high mobility scenario. When T_{slot} increases, it yields that the units in the scenario have lower moving velocity, and the number of available pilots P during T_{slot} increases proportionally.

The RRH keeps an ingress queue of all the active transmission requests. The BBU is able to keep track of the status of this queue. Every time the BBU gets updated queuing information, it sends a new scheduling decision so that the RRH could apply the updated allocation policy to the active CUs.

B. Traffic Model

Each CU$_k$, where $k \in \{1, 2, ..., K\}$, sends out the transmission requests at an average rate λ_k. We take into account the industry and IoT source level traffic models summarized in [10]. We use *Homogeneous periodic traffic* as the arrival process to generate transmission requests. By following this arrival process, each CU sends out requests with a nearly constant period around c but with a normally distributed noise, implying the average arrival rate of CU$_k$ is $\lambda_k = 1/c$. Each request has the following features:

- The CU ID k, indicating it is a request made by CU$_k$.
- The count γ, indicating it is the γth request made by CU$_k$.
- Deadline D_k^γ. The deadline length of CU$_k$ is sampled from an uniform distribution between c and D, where D is the bound of deadline lengths of all the CUs.

The overall average arrival rate to the system is then the sum of all sources $\lambda = K/c$. The offered load to the system only depends on the number of active CUs K in the scenario.

C. The Scheduling Policy

At the beginning of every coherence interval, the RRH sends the information of all the active requests in the ingress queue to the BBU pool. We denote the information sent by the RRH as the *report* in our model, which contains the CU ID and the deadline (k, D_k^γ) of all the active requests in the queue.

When the BBU pool receives a new report, it inspects the active request information in the queue and makes the corresponding *decision*, which is a set of CU IDs $\mathcal{K} \subseteq \{1, 2, 3, ...K\}$ to which the pilots are assigned. If the number of CUs with pending transmissions in the ingress queue is less than the available pilots P, it assigns all the CUs in the queue a pilot. If the number of CUs is greater than P, the EDF algorithm will be applied to allocate pilots to the P CUs whose requests have the earliest deadlines.

D. Fronthaul and Latency Model

The fronthaul link will cause a delay of each message sent over it. The round-trip delay of the fronthaul link is modeled as the duration from when a report departs to when the corresponding decision arrives at the RRH, but neglecting the computation time in the BBU pool for making the decision. The round-trip delay is modeled with a log-Laplace distribution with mean μ milliseconds. Our motivation for this choice is described in Section V-A.

E. Performance Metrics

In this section, we detail the performance metrics: *loss* and *pilot utilization*. The pilot utilization is calculated as follows. Given a time slot j, the RRH takes a decision that $\hat{P}_j$ pilots should be assigned to the CUs in set $\mathcal{K}_j$ waiting in line, where the length of set $\mathcal{K}_j$ equals to $\hat{P}_j$, $\hat{P}_j \leq P$ and $\mathcal{K}_j \subseteq \{1, 2, 3, ...K\}$. For each CU in set $\mathcal{K}_j$, the number of transmission requests that can be served is T_{slot}/T_c, as it is proportional to the coherence interval length. We denote the actual number of active requests from CU$_k \in \mathcal{K}_j$ in the queue by $N_{k,j}$. This means that in a time slot j, the number of wasted pilots $W_{k,j}$ for CU$_k$ is:

$$W_{k,j} = \begin{cases} 0 & \text{if } N_{k,j} \geq T_{slot}/T_c \\ \frac{T_{slot}/T_c - N_{k,j}}{T_{slot}/T_c} & \text{if } N_{k,j} < T_{slot}/T_c \end{cases} \tag{1}$$

This yields the pilot utilization in slot j:

$$U_j = 1 - \frac{\sum^{\forall k \in \mathcal{K}_j} W_{k,j}}{\hat{P}_j T_{slot}/T_c} \tag{2}$$

Taking the length of one simulation as T, the pilot utilization during the whole service period is:

$$U = 1 - \frac{\sum_{j=1}^{T/T_{slot}} \sum^{\forall k \in \mathcal{K}_j} W_{k,j}}{\sum_{j=1}^{T/T_{slot}} \hat{P}_j T_{slot}/T_c} \tag{3}$$

Denoting the actual number of requests from CU$_k$ being served in time slot j as $S_{k,j}$, the average loss of the system during T is given by:

$$\bar{L} = 1 - \frac{\sum_{j=1}^{T/T_{slot}} \sum^{\forall k \in \mathcal{K}_j} S_{k,j}}{\sum_{k=1}^{K} \lambda_k T} \tag{4}$$

$$\text{where } S_{k,j} = \min(T_{slot}/T_c, N_{k,j})$$

We denote this as $\bar{L}$ because it is calculated from the mean arrival rate λ_k of each CU. In the simulation experiments, we measured the actual number of transmission requests in the system to calculate the loss L.

TABLE I: Arrival process parameters for the evaluation on tolerable round-trip delay.

Parameter name	Value	Symbol
Arrival interval	10 ms	c_k
Number of CUs	20	K
Deadline length bounds	$\{5, 6, 8, 10, 12, 15\}$ ms	D

IV. SYSTEM EVALUATION

In this section, we present the experiment setup and the parameter values we used in the simulations to investigate the feasibility of deploying a C-RAN system in an industrial automation scenario. The simulation is implemented in Simpy[1]. We ran all the experiments to simulate a system time of $T = 200\,000$ms and there are 20 repetitions for each parameter set.

1) Latency: To give an intuitive illustration of the delay incurred by the C-RAN system, we measured the round-trip delay by pinging time-stamped UDP packets from an Ubuntu 18.10 LTS machine (representing the RRH) to a remote service function hosted by a docker container residing in a virtual machine in a data-center, which is 2km away from the the RRH, representing the BBU pool.

In our simulation, we used a log-Laplace distribution to generate the round-trip delays, which, as will be shown in Section V-A, is empirically modeled from our measurements. The mean μ of the round-trip delay varies from 0.5ms to 15ms, but the other distribution parameters remain the same for all experiments.

2) Loss: To evaluate if the C-RAN system can meet the minimal requirements from the industrial standards, here, we set the maximum permissible loss to 5% for all the transmission requests.

The loss is highly related to the CUs' tolerance on the waiting time to get a radio resource, and therefore we ran experiments with the objective of investigating the maximum round-trip delay that the CUs can tolerate when they have different deadlines. We set the variables of the CUs arrival process as shown in Table I. We choose a medium mobility scenario in this evaluation and the corresponding variables under this mobility scenario can be found in Table II.

To invetigate the maximum number of CUs that the system can serve under different mobility scenarios, we also ran the experiments when all CUs have deadline lengths the same as their arrival intervals indicated in Table I. We set the round-trip delay in this evaluation as 3ms, which, as will be shown in Section V-A, is slightly larger than our latency measurements from the aforementioned experiment setup.

3) Pilot Utilization: The pilot utilization becomes important once the requirement of loss is met. It is obvious that the loss decreases if the scheduler allocates redundant resources to the CUs. However, this could mean that the background traffic, which has lower priority than the CU traffic, may be faced with resource starvation due to pilot waste. Thus we should

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[1] https://simpy.readthedocs.io/en/latest/

TABLE II: Parameters related to different mobility scenarios in the simulation.

Mobility scenario	High	Medium	Low
Coherence interval length T_{slot}	0.5ms	1ms	1.5ms
Available pilots per interval P	12	24	36

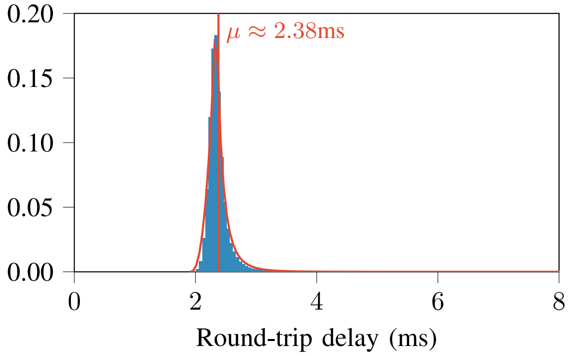

Fig. 3: The histogram of the UDP round-trip delay measurements. The red curve is the probability density function and the mean value fitted from the histogram.

consider pilot utilization under a low loss case, in which the length of deadlines has very little impact on the utilization, but the length of the coherence interval, or the CUs' mobility, becomes the dominating factor. Thus we ran the experiments under different mobility scenarios but with the parameters of the CUs' arrival processes the same as in Table I, except for the deadline length, which in this case has an upper bound fixed to 15ms. The longest round-trip delay is set to 8ms, in which case there are rare discarded requests in the system for this deadline. loss

V. Experiment Results

In this section, we show our latency measurements and the simulation results regarding the two performances metrics *loss* and *pilot utilization* by following the evaluation setup.

A. Round-trip Delay

Fig. 3 shows the histogram of our round-trip delay measurements. We fitted the histogram to a log-Laplace distribution with mean value $\mu \approx 2.38$ms. This is a long-tailed distribution, which is not just incurred by the separation between the RRH and the BBU pool, but also by the cloud execution environment.

B. Loss

Fig. 4 shows the maximum round-trip delay the system can tolerate so that the loss is under 5% when the CUs have the arrival processes indicated in Table I. As we can see from the Fig. 4, the tolerable delay is always 1-3ms less than the deadline length. If one expects each CU to have a deadline the same length as its period, the round-trip delay incurred by the C-RAN system can not be longer than the CU's transmission interval.

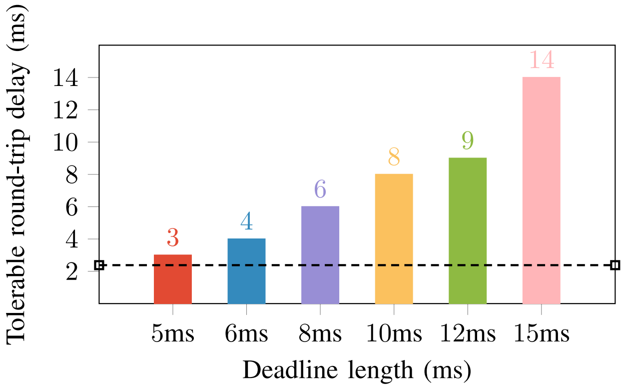

Fig. 4: The tolerable round-trip delay with varying CU deadline lengths. There are in total 20 CUs, all with medium mobility. The dashed line indicates the mean round-trip delay from our measurements shown in Section V-A.

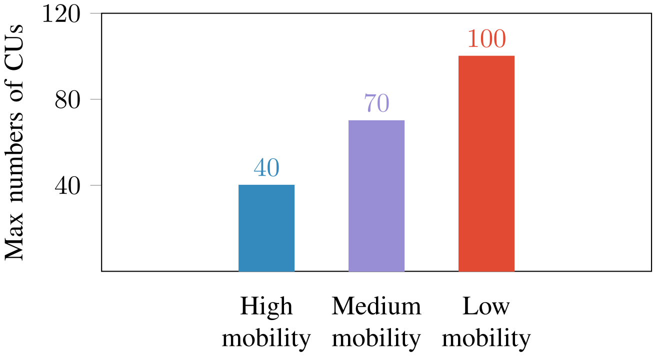

Fig. 5: Maximum number of CUs the system can serve within the allowed loss of 5% under different mobility scenarios. Each CU has a deadline length of 10ms and the system round-trip delay is 3ms.

Fig. 5 shows the maximum number of CUs that the system can serve within the allowable loss of 5%, when all CUs have deadline length of 10ms and the round-trip delay in the system is 3ms. As can be expected, the system can serve more units when the mobility is lower (that is, when the coherence interval is longer). We can conclude from the figure that when the units have low mobility, the system can handle a higher offered load from the CUs without loss than when in a higher mobility scenario.

C. Pilot Utilization

Fig. 6 shows how the pilot utilization is affected by the CUs mobility and the delay. When there is no delay in the system, a short coherence interval can achieve full pilot utilization. But as the interval gets longer, the utilization of the resources drops significantly to only 40% when there is only 0.5ms round-trip delay in the system. This is because when the allocation slot is shorter, the decisions are more frequently made so that they can better follow the dynamics of the ingress queue. However, having longer intervals means more time-

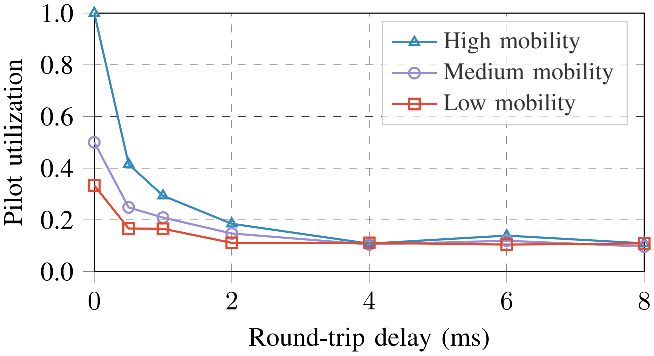

Fig. 6: The pilot utilization when the number of CUs is $K = 20$ and each has a deadline length between 10 and 15ms.

frequency space resource are reserved for the same set of CUs in each slot. Since the transmission periods of the CUs are usually longer than the length of an allocation slot, this leads to redundant allocations when the number of the pending requests in the queue is less than which can be served by the system. However as the round-trip delay between the RRH and BBU pool increases, which may cause outdated reporting about the queuing status, the pilot utilization converges to only 10%. In this case, the length of coherence intervals has less impact, since the misreporting due to the latency causes faulty allocations, in which case a CU is allocated a pilot according to the latest arrived decision, even though all its requests were already served by previous decisions.

VI. CONCLUSIONS

In this paper, we addressed the latency issue incurred by the C-RAN system characteristics and demonstrated the feasibility of deploying such a system under the industrial criteria. We considered a pilot scheduling function for industrial critical units that have stringent requirements on the deadlines. The function is hosted in the BBU pool but the pilots need to be allocated to CUs by the RRH. We focused on two performance metrics *loss* and *pilot utilization* and applied a simple EDF scheduling policy to evaluate if the system can cope with the delay between the scheduling function and the allocation. We performed a simulation to investigate the behavior of the system in different scenarios.

Our experiment results have shown that the C-RAN system is feasible to deploy for the industrial automation scenario, where the CUs can tolerate round-trip delays up to 2ms less than their own deadlines. For a massive MIMO RRH, lower mobility end-users lead to a longer coherence interval and bring lower loss, implying that when the units' mobility is low in the scenario, the system is capable of serving a higher number of CUs simultaneously. On the other hand, both delay and a longer coherence interval lead to a huge amount of resource waste, which may lead to resource starvation of the background traffic.

The next step of our work is to develop a new scheduling strategy to avoid redundant and faulty allocation so that the resources can be better utilized and the system can meet more stringent reliability requirements in industrial communication.

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