Exploiting Diversity for Ultra-Reliable and Low-Latency Wireless Control

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Abstract—This paper introduces a wireless communication protocol for industrial control systems that uses channel quality awareness to dynamically create network-device cooperation and assist the nodes in momentary poor channel conditions. To that point, channel state information is used to identify nodes with strong and weak channel conditions. We show that strong nodes in the network are best to be served in a single-hop transmission with transmission rate adapted to their instantaneous channel conditions. Meanwhile, the remainder of time-frequency resources is used to serve the nodes with weak channel condition using a two-hop transmission with cooperative communication among all the nodes to meet the target reliability in their communication with the controller. We formulate the achievable multi-user and multi-antenna diversity gain in the low-latency regime, and propose a new scheme for exploiting those on-demand, in favor of reliability and efficiency. The proposed transmission scheme is therefore dubbed adaptive network-device cooperation (ANDCoop), since it is able to adaptively allocate cooperation resources while enjoying the multi-user diversity gain of the network. We formulate the optimization problem of associating nodes to each group and dividing resources between the two groups. Numerical solutions show significant improvement in spectral efficiency and system reliability compared to the existing schemes in the literature. System design incorporating the proposed transmission strategy can thus reduce infrastructure cost for future private wireless networks.

Index Terms—Ultra-reliable low-latency communications, factory automation, industrial internet-of-things, 5G

I. INTRODUCTION

A. Industrial Wireless Control

Wireless industrial internet-of-things (IIoT) in the next generation of industrial control systems require communications with sub-ms, extreme low latency and “cable-like” ultra-high reliability. For a large-scale network of sensor and actuator devices in factory automation applications, different wireless transmission schemes have recently been proposed to exploit spatial and multi-user diversity gain in the network. The challenge in this new paradigm of wireless communication is that the design requires guaranteed service to all, including the weakest user, as opposed to the classic paradigm of network design that targets average performance. Traditionally, such industrial automation requirements are realized on the factory floor through wired communications e.g., using fieldbus and Ethernet based solutions. The wired solutions, however, are considered to be cumbersome and expensive in many applications. Moreover, the future industrial automation targets a highly flexible and dynamic environment of production stations that support robotic mobility to be able to seamlessly re-arrange according to production requirements[1]–[3]. As a result, there is an increased desire to replace wired communication systems for factory automation with wireless alternatives to reduce bulk as well as installation and maintenance costs[4]. This calls for innovative solutions in contrast to existing wireless technologies that are designed for delay tolerant consumer solutions, making them unsuited for industrial automation[5]. In the era beyond the fifth generation (5G) mobile networks, ultra-reliable low-latency communications (URLLC) is promised to deliver such demanding requirements using the advanced physical layer technologies, including communications in millimeter-wave (mmWave) and Ultra Wideband (UWB) spectrum access[6], [7], accompanied by the improvements in network architecture in bringing the cloud close to the edge to reduce latency, and using machine learning for a fast and reliable prediction of channels and traffic[8].

B. Prior Work

To fulfill the requirements of ultra-high reliability within a stringent latency constraint, different diversity techniques are suggested in the literature. Time and frequency diversity techniques[9] as well as spatial diversity and multi-user cooperation[10] can reduce the required reliability-achieving signal to noise ratio (SNR). For example, the importance of multi-antenna receive diversity in improving reliability and coverage was pointed out in[11]. In low-latency industrial automation applications, the cycle time is shorter than the fading channel coherence time, which rules out viability of automatic repeat request (ARQ)-based time diversity techniques[12]. In[10], it is shown that relying solely on frequency diversity to achieve $10^{-9}$ error rate requires impractically high SNR values in realistic channel conditions. It is further shown that multi-user diversity, even in low or moderate SNR regime, can achieve ultra-reliability. Incidentally, increasing transmit diversity by engaging multiple transmitting access points (APs), similar to coordinated multi-point (CoMP) technology[13], is also not a straightforward path to reliability. In fact, in the absence of channel state information (CSI) at the transmitter, transmit diversity falls dramatically short of achieving high reliability as discussed in[14]. The study in[14] further shows that by using CSI to adapt transmission rate at the transmitter, the inherent multi-user diversity gain of a large size network...
can be exploited to achieve high reliability. To that point, the cooperative transmission in [10] attempts to exploit the full potential of wireless network by enabling cooperative device-to-device relaying to improve reliability. The focus of [10] is to devise transmission schemes that do not require transmitter CSI. Such CSI-agnostic schemes are not able to take the differences in the instantaneous channel conditions into account, resulting in a sub-optimal and conservative choice of transmission rate determined by the worst user’s conditions, and loss of spectral efficiency. On the other hand, in a multi-user wireless network, the overhead for acquiring CSI can grow large as the size of the network grows. The works in [15] and [14] study the impact of such overhead. Particularly, [15] considers the overhead of CSI acquisition when communicating with small packets, thus characterizing the error performance under the finite block length regime.

System-level simulations for multi-user networks under URLLC requirements is highly time-consuming and complex. We acknowledge that several works in the literature have addressed and dealt with those complexities, including [16], [17], and have provided insightful conclusions for system design of cellular networks with extreme reliability requirements.

C. Exploiting Diversity “On-demand”

Spatial diversity transmission, as the most dependable source of achieving high reliability when communicating over fading channels, is a viable solution for reliability that may be achieved by using multiple transmission points or antennas. In low cost deployments, however, it is desirable to have a small number of spatially distributed, simple APs with limited number of antennas. Spatial diversity transmission, however, needs to also exploit multi-user diversity stemming from the fact that several users with different channel conditions are part of the communication system. On the other hand, cooperative relaying among users (as proposed in [10]) essentially also achieves spatial diversity through multi-user diversity.

The core question this paper tries to answer is how to use channel awareness at the transmitter to efficiently allocate radio and cooperation resources, and to exploit diversity according to the instantaneous needs of the users. We introduce a transmission protocol that is capable of identifying users’ channel strength and allows for exploiting different sources of diversity, on demand. We propose to adapt the transmission rate for users with strong channel from the APs according to their channel, while exploiting cooperative diversity for the remaining users with weak channel. This introduces a robust way of deploying the emergency resources of network cooperation, only for the devices that absolutely need them. We study the improvements offered by this protocol on the operating spectral efficiency and the minimum required SNR for reliability. In high SNR, this impacts the slope of the outage probability curve and improves diversity order by deploying network-device cooperation for the poor links. Meanwhile, it brings better multiplexing gain by smartly exploiting the difference in channel conditions.

D. Channel Estimation in Wireless Networks

We assume a general transmission framework where data is accompanied with proper amount of pilot signal in all transmissions [18]. The estimated channel at a receiving node can then be reported back to the transmitting node, e.g. in form of channel quality indicator (CQI). With an adequate frequency of CQI updates, transmitter can improve resource utilization efficiency by adapting the transmission attributes to the channel. In fact, such an approach is widely adopted in multi-user cellular technologies such as the long term evolution (LTE) and new radio (NR). More interestingly, by assuming channel reciprocity in time division duplex (TDD) transmission mode for the industrial wireless control problem of our interest with isochronous traffic pattern in the down-link (DL) and the up-link (UL) directions, CQI acquisition requires no feedback exchange between the nodes. Instead, CQI can be estimated when the node performs channel estimation while in receiving mode and can be used when the node switches to transmit mode. In this paper, we adopt this assumption and present a new transmission protocol that utilizes channel state information to best exploit sources of diversity in the wireless network.

E. Contributions

The objective of this paper is to design an ultra-reliable transmission scheme for extreme low-latency applications which uses minimal control signaling for scheduling. To this end, we aim to exploit full spatial and multi-user diversity potential of the network in favor of system reliability and spectral efficiency. Our contributions are summarized as follows.

- We identify and analyze different sources of diversity gain for ultra-reliable wireless communications in an industrial wireless control network. A network with multiple fully-connected APs is assumed where the APs coordinate their transmissions similar to CoMP. We formulate the achievable multi-user and multi-antenna diversity gain in the low-latency regime, and propose a new scheme for exploiting those in favor of reliability and efficiency.

- A new ultra-reliable transmission scheme dubbed adaptive network-device cooperation (ANDCoop) that exploits different sources of diversity in the network is introduced. The proposed scheme uses the approximate knowledge of CSI to categorizes the devices into two groups, namely, group of devices with strong instantaneous channel, and the group of devices with weak channel. The two groups are then scheduled in separate scheduling phases: first, each of the strong devices receives its DL message with a unique transmission rate that is adapted to its instantaneous channel state; next, the second group of devices are scheduled with a fixed rate through two-hop cooperative transmission where all the devices in both groups can potentially contribute in as decode-and-forward (DF) relays.

- Reliability performance of the proposed transmission scheme is analytically formulated, in order to characterize the system outage probability. The analysis is then extended to diversity-multiplexing trade-off, where closed-
form formulations for the achievable diversity order are derived. We further formulate the optimization problem of allotting time between the two scheduling phases and provide numerical solutions to the optimization problem.

- Comprehensive and detailed system-level simulations are reported to identify guidelines for optimal system design. The proposed protocol is compared against the existing transmission protocols in the literature. The numerical analysis demonstrates significant concurrent improvement in spectral efficiency (approximately 0.5 bits per channel use (bpcu) per AP antenna) and reliability. Alternatively, under fixed spectral efficiency setup, the proposed algorithm achieves the desired reliability at significantly smaller transmit power (around 15 dB improvement compared to the existing schemes), while utilizing around 40% less relay nodes’ energy, which in turn reduces the interference footprint. Moreover, the impact of CSI estimation error is carefully studied, suggesting that the proposed ANDCoop transmission scheme consistently reduces the impact of such error on system reliability, thanks to the strategy of grouping devices according to channel quality. We identify significant potential in cost reduction for the future private industrial wireless control network, thanks to the improved operation efficiency using the proposed ANDCoop scheme.

F. Organization of the Paper

The sequence of this paper is as follows: in Section III we present the problem description and the assumed network setup; further, we provide motivations for designing a new ultra-reliable transmission scheme; in Section III the proposed channel-aware URLLC solution is presented and analyzed for outage probability and diversity order; Section IV presents and discusses the numerical analysis of the proposed scheme; and finally, Section V covers the concluding remarks.

II. PROBLEM SETUP

In this section, we first describe the communications system model of interest and highlight the main system assumptions we use in our analysis. Then, we discuss exploiting diversity gain a multi-user wireless network under the paradigm of ultra-reliable communications to motivate our design target in exploiting full diversity potential of the network for industrial wireless control.

A. System Model

Network: \( N \) devices are scattered on a factory floor and are wirelessly connected with the controller APs. Fig. 1 illustrates the considered network where a controller is wired to \( M \) fully synchronized APs. This paper considers a CoMP setting where all APs are synchronized and they coordinate their transmission attributes for transmission to every device. All the communicating nodes have a single antenna for transmission and reception. Every device expects an independent \( B \) bytes of data to be delivered every \( T \) seconds over a bandwidth of \( W \) Hertz. We use \( \eta = \frac{\text{bpcu}}{\text{W}} \), measured in bpcu, to denote the overall spectral efficiency of the system. Let \( \mathcal{A} = \{1, 2, \ldots, M\} \) denote the set of APs, where \( M = |\mathcal{A}| \) is the number of APs. Similarly, let \( \mathcal{D} = \{1, 2, \ldots, N\} \) be the set of device IDs where \( N = |\mathcal{D}| \). Throughout the paper, we reserve the letter \( R \) to denote transmit rate measured in bits per second (bps).

Channel dynamics: Wireless channels linking every AP-device and device-device pair are assumed to undergo independent frequency-flat Rayleigh fading. We note that this assumption is adopted for analytical tractability, although measurement campaigns for industrial environments show frequency-selectivity over wide bandwidth [19], [20]. We assume a setting where each time-cycle experiences a constant channel which fades independently from one cycle to the next. Let \( h^a_{i,j} \) and \( \rho^a_{i,j} \) denote the channel fade random variable and the average received SNR (which includes the effect of path loss and is averaged with respect to fading distribution) of the transmission from AP \( i \) to device \( j \), where \( i \in \mathcal{A} \) and \( j \in \mathcal{D} \). We use \( g^a_{i,j} = \rho^a_{i,j} |h^a_{i,j}|^2 \) to denote the instantaneous received SNR. Similarly, let \( h^d_{k,j} \), \( \rho^d_{k,j} \), and \( g^d_{k,j} \) denote the same variables for the link from device \( k \) to device \( j \), where \( k, j \in \mathcal{D} \). Note that \( \rho^d_{k,j} = P_a/(|W \cdot \sigma_0|) \) and \( \rho^d_{k,j} = P_d/(|W \cdot \sigma_0|) \), where \( P_a \) and \( P_d \) denote the transmit power of an access point and a device, respectively, and \( \sigma_0 \) denotes power spectral density (PSD) of the additive white Gaussian noise (AWGN).

Outage model: A device is said to be in outage if the transmission rate \( R \) exceeds the instantaneous channel capacity, and is considered successful otherwise. We assume distributed space-time coding that collects spatial diversity through summation of the received signal powers from all transmitters. Therefore, with \( C_j \) denoting the set of nodes cooperatively transmitting with rate \( R \) to node \( j \) over bandwidth \( W \), the transmission fails if

\[
W \log \left( 1 + \sum_{k \in C_j} g^d_{k,j} + \sum_{i \in \mathcal{A} \cap C_j} g^a_{i,j} \right) < R. \tag{1}
\]
The expression in (1) implicitly assumes long block-length transmission. While admittedly, the transmission of small packets in line with what is typically expected in URLLC scenarios and also suitable for the block-fading model challenges the assumption that the packets are long enough for (1), we note that the impact of such assumptions can be further evaluated by adopting the finite block-length regime outage models [21]. More importantly, the recent findings in [22] suggest that in a fading channel, the effect of outage dominates the effect of short block-length, so the outage capacity is in fact a fair substitute for the finite block-length fundamental limits. For this reason, the rest of this paper focuses on the outage model in (1).

Similar to the previous works in [10], [23], [24], we analyze system outage probability as the key performance metric, denoted by $P_{out}(.)$ and defined as the probability that at least one device fails to decode its own message at the end of time-cycle $T$. This is a more appropriate measure for reliability of communication in an industrial wireless control setup compared to e.g., average outage probability across devices. The argument is that the industrial wireless control system may only continue its operation when all devices follow the controller instructions, and the system fails if at least one device fails. Note that $P_{out}(.)$ is a function of the channel random variables, as well as the parameters of the system. Moreover, such definition complies with the joint definition of reliability and latency requirements in the context of URLLC.

In essence, a URLLC system satisfies its requirements only if it can guarantee the desired reliability level within the desired latency budget [25]. Therefore, in this work, instead of the statistics of the experience delay, we are interested in the outage probability within a constrained latency of $T$ seconds.

Diversity-multiplexing: It is widely accepted that the end goal of URLLC systems is to increase reliability, and therefore, the system outage probability curve is the natural benchmark for performance evaluation. However, the true performance of such system can only be evaluated if data rate is monitored alongside the reliability. Thanks to the choice of system outage probability (described above) to represent error rate in the system model, the diversity gain can be captured as the slope at which the error rate decays in the high SNR regime. Moreover, we define the multiplexing gain $r$ as the ratio at which the payload size per device $B$ increases with transmit power $P_t$ in log scale, i.e., $B \propto r \log P_t$. Thus, the dual benefits can be captured by the diversity-multiplexing tradeoff in the high SNR regime, where similar to [26], [27], we say that a diversity gain $d(r)$ is achieved at multiplexing gain $r$, if

$$d(r) = \lim_{P_t \to \infty} \frac{\log P_{out}(r \log P_t)}{\log P_t},$$

thus capturing the tradeoff between data rate increase (i.e., $r$) and diversity order, in high SNR.

Channel estimation: We assume instantaneous CSI of the AP-device pairs are present at the controller in the form of link strength $g_{i,j}$'s, which doesn’t require the knowledge of channel phase. This can be for instance provided by frequent transmission of uplink pilot sequences by the devices similar to sounding reference signal (SRS) in LTE. Each AP estimates its channel from all the devices, using those pilot sequences. The CSI will be used to identify groups of devices with strong and weak channel conditions and to adapt the transmission rate for the former group. The variance of channel estimation error can be arbitrarily minimized by increasing the number of pilot sequences and transmit power of the pilots [14], [18], [28].

Assuming that the channel SNR, $\rho$, is known, we use $\hat{h}$ and $\hat{g}$ to denote the estimated channel fade and estimated SNR, respectively. We further use $L$ to denote the length of the pilot training sequence for each device, with duration of $T_P = L \cdot T_S$ seconds over orthogonal time-frequency resources, where $T_S = 1/W$ is the symbol period. The total overhead cost of pilot transmission then equals to $N \cdot T_P$, and is paid out of the time budget $T$, leaving $T_P = T - N \cdot T_S$ seconds for data transmission. Using recursive minimum mean-square-error (MMSE) channel estimation [18], [28], the true Rayleigh fade $h$ can be written as $h = \bar{h} + \epsilon$, where $\epsilon \sim \mathcal{CN}(0, \sigma_e(L))$, $\bar{h} \sim \mathcal{CN}(0, 1 - \sigma_e(L))$, and

$$\sigma_e(L) = \frac{1}{1 + L \cdot \rho}.$$  

With respect to channel estimation, and for completeness of the investigation, we adopt two scenarios in this paper: namely, genie-aided perfect CSI (P-CSI), i.e., where fade is perfectly estimated as $\bar{h} = h$, at the cost of zero pilot overhead $L = 0$, leaving $T_P = T$; and the case of imperfect CSI (I-CSI), where channel estimation error is a function of the pilot training sequence length $L$ based on [3], resulting in $T_P = T - N \cdot L \cdot T_S$.

Notations: Throughout the paper, we use the notations listed in Table I.

B. On the Role of Multi-User Diversity in Low-Latency Regime

In a large network with multiple users, each fading independently, there is likely to be a user whose channel is near its peak, at any time. This can be utilized to maximize the long term total throughput by use of CSI feedback and always serving the user with the strongest channel [29], [30], hence, exploiting multi-user diversity gain. Similarly, for a given spectral efficiency, the per-user reliability of transmission can be maximized by choosing the user with strongest channel at any time. Therefore, with loose latency requirement, multi-user diversity gain is a natural source of reliability and efficiency. However, in low-latency regime, where tolerated latency is smaller or equal to the channel coherence time, it is likely to have one or few users whose channels are poor, at any time. It is therefore challenging to exploit multi-user diversity while guaranteeing timely reliability to multiple users with asymmetric channel statistics.

To further analyze the diversity gain in low-latency regime, let’s assume the network setup described earlier in this section with $M = 1$, where all the channel gain $g_{i,j}$'s are perfectly known and thus, the controller can precisely determine the achievable rate $c_j$ for device $j$, and the AP targets an average spectral efficiency of $\frac{\lambda}{T}$ in each time cycle $T$, with equal
packet size for every scheduled device. Let’s consider the case where the scheduler has the complete freedom to choose any nonempty subset of the $N$ devices in each time cycle. We model the average latency based on $K$, the number of users that are scheduled within a given time cycle. The average experienced latency by a device to be scheduled can be shown to be $\frac{1}{N/K}$. For example under round-robin scheduling, by scheduling all devices in every time cycle $T$, i.e., $K = N$, the average latency is $T$, and by scheduling only one device in each time cycle the average latency is increased to $\frac{N+1}{N}T$. The scheduler is thus rewarded with reduced average latency, for scheduling every additional device out of the $N$. The cost of scheduling an additional device is going to be a loss in the collected multi-user diversity order. The following proposition addresses the trade-off between average latency and the collected multi-user diversity gain, assuming independent and identically distributed (i.i.d.) Rayleigh fading on every link.

**Proposition 1.** The maximum diversity order exploited at zero multiplexing point by the scheduler described above for scheduling exactly $K$ users in each time cycle is $N - K + 1$ for the case of $M = 1$, and $M(N - K + 1)$ for general $M$.

**Proof.** See Appendix A.

In other words, with strict latency requirements, i.e., all the $N$ devices must be scheduled over one coherence time, which is the case for an industrial wireless control network as described earlier in this section, then the system experiences diversity order of 1 (for the case of $M=1$), meaning that no multi-user diversity gain is exploited. On the other hand, the maximum multi-user diversity order of $N$, is only exploited when the latency requirement is maximally loose and the controller gets to schedule the best device in each time cycle. Midway, the controller can trade off latency with diversity order by transmitting to $K \leq N$ devices over each coherence time, thus gaining the diversity order of $N - K + 1$. In fact, as we see in the Section III the transmission protocol proposed in this paper benefits from such trade-off in exploiting the multi-user diversity gain by scheduling a subset of the devices with the highest channel strengths. For the remaining devices, the protocol seeks for the gain of cooperation among nodes, which is the topic of the following discussion.

### C. Motivation for Multi-Hop Transmission

Cooperative relaying has been studied recently in several works as an enabler of URLLC, e.g., see [10], [31]–[33], leveraging on the spatial diversity gain from engaging multiple relay devices, which increases robustness to fading variations. The focus of the design in cooperative relaying scheme in [10] has been to mitigate the effect of small-scale fading. Such approach is highly beneficial in absence of multiple-input multiple-output (MIMO) techniques. However, with increasing deployment of massive MIMO, in practice, those benefits can be largely undermined. Particularly, cellular communication technologies typically rely on channel hardening effect of MIMO to mitigate the effect of small-scale fading [34].

Nevertheless, multi-hop relaying has historically been considered as a means of extending coverage in various wireless technologies, such as worldwide interoperability for mi-
crowbar access (WiMax), LTE, and recently in 5G NR, e.g., see [15]–[19]. The coverage problem caused by static or mobile blockages is in fact a challenging issue in industrial environments. Blockage can generally impede the link SNR by obstructing the line-of-sight (LOS). More significantly, when blockage size is several times larger than the electromagnetic wavelength, the diffraction around the obstacle becomes weaker, making the impact of blockage stronger. Consequently, blockages becomes a more severe challenge in higher frequencies, or the so called mmWave [40]. Moreover, the dynamic nature of factory floor with large number of static and moving objects makes it difficult to provide every time/everywhere wireless link availability. This further motivates the use of cooperative relaying to deal with temporary and/or zonal loss of coverage.

To this point, the example in Fig. 2 illustrates the SNR and coverage of $10^{-9}$ outage probability for spectral efficiency of 1 bpcu in an area of $100 \times 100$ m$^2$, in presence of a blockage (cyan color wall); the bright point in the center locates the AP while the rest of the bright points locate the relay devices; (a) AP with 4 antennas in the center provides 95.5% when transmitting over the full time cycle $T$, i.e., transmission rate of 1 bpcu; (b) on the left, 87.95% coverage from an AP with 4 antennas at transmission rate of 2 bpcu, over first $T/2$ duration; on the right, 72.1% coverage using three single antenna relay devices at transmission rate of 2 bpcu, over the second $T/2$ duration; 100% combined coverage of the two phases.

Knowing that the blockage affects the coverage around the right hand side of the square area, such coverage enhancement from two-hop relaying can in practice be directed towards devices in the same area. This in fact increases the efficiency of ultra-reliable communications, by deploying the cooperative relaying in an on-demand fashion, only for the devices with coverage issues.

Improving coverage for IIoT applications can alternatively be done by densification of the APs. However, over-provisioning is not efficient in terms of the cost of the network deployment. It should be noted that the intention of the example in Fig. 2 is not to claim that two-hop cooperative relaying is always better than single-hop transmission. In fact, as we will discuss in the following sections, with a smart and dynamic algorithm to use the cooperative relaying gain in an on-demand manner, the overall spectral efficiency can be improved compared to the case where all the devices are served with two-hop transmission.

### III. Proposed Channel-Aware Transmission Protocol

In this section we first introduce the proposed transmission protocol. Then outage and diversity order analysis of the protocol are presented.

#### A. Transmission Protocol

The total DL transmission time $T_{D}$ is divided into two parts, using a partitioning factor $0 \leq \beta \leq 1$, where $T_{D} = \beta T_{D}$ is used for rate-adaptive single-hop transmission of independent messages to devices with strong instantaneous channel to the controller APs in a time-division multiple access (TDMA) fashion. The remaining $T_{D} = (1 - \beta)T_{D}$ is used for two-hop cooperative transmission phase to the rest of the devices, where the messages of all remaining devices are aggregated and transmitted in two hops. In addition, the controller acquires
the knowledge of $\hat{g}_{i,j}^a$’s for the AP-device pairs via channel estimation using pilots of length $L$. Based on this, devices are put in an order according to the instantaneous transmission rate that they can receive at from the APs. The achievable transmission rate for device $j$, $c_j$, can be computed using (1).

The controller estimates the achievable rate, using

$$\hat{c}_j = W \log \left( 1 + \sum_{i \in A} \hat{g}_{i,j}^a \right).$$

Note that, for I-CSI, i.e., $\sigma_e > 0$, $\Pr(\hat{c}_j > c_j) = 0.5$. In other words, regardless of the channel estimation precision, the estimated transmission rate is above the achievable rate 50% of the time. To curb the impact of channel estimation error in case of I-CSI, we use a rate back-off parameter $0 \leq \theta \leq 1$ to adjust the transmission rate to $\theta \cdot \hat{c}$. The following definition denotes the largest subset of the devices that the controller can accommodate with single-hop transmission over time $\tau$.

$$S(\tau, \{\hat{g}_{i,j}^a\}) = \arg \max_S \frac{1}{|S|} \sum_{\ell \in S} \frac{1}{\theta \cdot \hat{c}_j} \leq \frac{\tau}{\beta},$$

subject to $\forall k \in D \setminus S$, $\forall j \in S$. 

Let $D_{1h}$, where $D_{1h} \subset D$, and $D_{2h} = D \setminus D_{1h}$ denote the random set of the strong and weak devices, respectively. Let $K_{1h} = |D_{1h}|$ and $K_{2h} = |D_{2h}|$ be the discrete random variables of size of those sets, which follows $K_{1h} + K_{2h} = N$. Let $R_{1h,j} = \theta \cdot \hat{c}_j$ denote the transmission rate for device $j \in D_{1h}$. We assume that $\beta$ is known by all the nodes in the network. Therefore, upon generating the set $D_{1h}$ for a given realization of the channels, the controller sends the set of indexes in $D_{1h}$ and the transmission rates $R_{1h,j}$, over a control channel to the strong devices. Such information is necessary for the devices to be able to follow the scheduling order of transmission in the single-hop phase. The devices in $D_{2h}$ are then scheduled over a two-hop transmission over the remaining $T_{2h}$, where their messages are aggregated, and $\alpha \cdot T_{2h}$ and $(1 - \alpha) \cdot T_{2h}$ are used for broadcasting and relaying the aggregated messages respectively, with $0 \leq \alpha \leq 1$.

In Fig. 3 the time scheduling of the proposed ANDCoop transmission protocol is illustrated. In the following the proposed ANDCoop transmission protocol is summarized. We assume that the controller has the knowledge of the appropriate $\beta$ and $\alpha$ design parameters, which are acquired off-line and are shared with the devices (we discuss the optimization of those parameters in the following subsection). A summary of the proposed algorithm in each time cycle is as follows:

1) Using the knowledge of AP-device CSI, the controller finds the set of devices, $D_{1h}$, that will be scheduled over single-hop rate-adaptive transmission. This is done according to $D_{1h} = S(T_{1h}, \{\hat{g}_{i,j}^a\})$ in [5], while $T_{1h} = \beta \cdot T$.

2) The controller adapts transmission rate for each device in $D_{1h}$ according to their instantaneous channel by setting

$$R_{1h,j} = \theta \cdot \hat{c}_j,$$

thus allocating $B/R_{1h,j}$ seconds of the total time for transmission to device $j$. The controller APs will then perform CoMP transmission of the message for each node $j \in D_{1h}$ with the adapted rate in a TDMA fashion.

3) All the $B$-bit messages intended for devices in $D_{2h} = D \setminus D_{1h}$ are aggregated together. The controller APs jointly broadcast the aggregated message at rate $R_{2h,b} = \frac{BK_{2h}}{\alpha T_{2h}}$, over the first $\alpha$ portion of $T_{2h}$ time.

4) All devices in $D$ attempt decoding the broadcast message from previous step. The successful devices to decode will act as relays.

5) The APs broadcast the message from step 3 at rate $R_{2h,r} = \frac{BK_{2h}}{(1-\alpha) T_{2h}}$. The relay devices from step 4 re-encode with the same code rate, and cooperate as simultaneous relays.

B. A Note on Optimization of the Design

The proposed transmission protocol can be optimized based on the design parameters $L$, $\beta$ and $\theta$, to achieve the minimum $P_{out}$. We perform numerical optimization in two scenarios of PCSI and I-CSI. Note that in P-CSI scenario, we fix $L = 0$ and $\theta = 1$, only optimizing with respect to $\beta$, for given transmit power and spectral efficiency. To this end, we fix the value of the time division parameter $\beta$ for all realizations of the channel. Therefore, we are able to numerically optimize $\beta$ for a given setup by running the simulation for all values of $\beta$ from a finite set of real numbers uniformly chosen from the $[0, 1]$ interval to derive $\hat{\beta} = \arg \min_{\beta} \mathbb{P}_{out}(\beta)$.

Optimization of the I-CSI scenario with exhaustive search across $L$, $\beta$, and $\theta$, is computationally costly. However, as we will show in the next section, parameter $L$ can be fixed with marginal effect on the outage, which can significantly reduces the search for the optimal $L$, $\beta$, and $\theta$.

Parameter $\alpha$ is used to partition the time $T_{2h}$ between broadcast and relaying hops of the two-hop cooperative transmission. Increasing $\alpha$ results in smaller $R_{2h,b}$, which increases chances of decoding for all nodes and results in larger expected number of relay nodes for the second hop. In turn, it will increase $R_{2h,r}$ and decrease chance of decoding in the second hop.

In practice, the messages can be concatenated before encoding which will potentially increase coding gain and reduce number of decoding attempts for relay devices.
hop. We note that the optimization of $\alpha$ is not a trivial problem however, following the observation in [10], the average reliability gain from optimizing $\alpha$ with respect to $\alpha = 0.5$ can be marginal, therefore, in the numerical analysis that will follow, we fix $\alpha = 0.5$.

C. Outage Analysis

We analyze system outage probability of the proposed system, denoted by $P_{\text{out}}$ and defined as the average probability that at least one device fails to decode its own message at the end of time-cycle $T$. Let $P_{\text{th}}(D_{1h})$ and $P_{\text{th}}(D_{2h})$ denote the probability of outage for at least one device in, respectively, the adaptive-rate single-hop phase and the two-hop cooperative phase of the transmission protocol.

**Single-hop rate-adaptive transmission:** Conditioned on CSI, we have

$$ P_{\text{th}}(D_{1h} | \{\hat{h}_{ij}\}) = \Pr(\exists j \in D_{1h}, \theta \cdot c > c), $$

where expectation is over channel gains. For the case of I-C SI with channel estimation error, the outage probability in (6) is non-zero as also discussed in [23] Sec. III-A]. Characterization of $P_{\text{th}}$ is not analytically tractable. However, when $\beta = 1$, i.e., all the devices are scheduled with single-hop transmission, outage probability is equivalent to the probability of *time overflow*, i.e., the chance that $T_{1h}$ is too short given the channel gains to successfully accommodate all the packets. In this case, analytical bounds on the outage probability can be found in [23], where it is shown that in practical ranges of SNR, as cell load $N \times B$ grows, the chance of time overflow increases above URLLC target outage probability and dominates system outage regardless of the precision of channel estimation.

For the case of P-CSI, when $\beta < 1$, all the devices in $D_{1h}$ pass the success condition in (11), resulting in $P_{\text{th}}(D_{1h} | \{\hat{h}_{ij}\}) = 0$. Therefore, the following is valid for P-CSI scenario.

$$ P_{\text{th}}(D_{1h} | \{\hat{h}_{ij}\}) = \begin{cases} 0 & 0 \leq \beta < 1 \\ \Pr(\sum_{j \in D} \frac{1}{c_j} > T_{1h}) & \beta = 1. \end{cases} $$

(7)

**Two-hop cooperative transmission:** Conditioned on CSI, the outage probability of the two-hop phase is given by

$$ P_{\text{th}}(D_{2h} | \{\hat{h}_{ij}\}) = \Pr(\exists j \in D_{2h} \setminus \mathcal{R} : \sum_{k \in \mathcal{R}} g_{ij,k}^a < \zeta), $$

where $\zeta = \frac{2R_{2h}}{1} - \sum_{i \in A} g_{ij}^a - 1$, and $\mathcal{R}$ is the set of relay devices, defined as

$$ \mathcal{R} = \{ j \in D : R_{2h,b} \leq c_j \}. $$

(8)

Although, averaging $P_{\text{th}}(D_{2h} | \{g_{ij}^a\})$ over channel gains is not analytically tractable, for the purpose of analyzing the diversity order gain of the transmission protocol, we are interested in the outage probability when all devices are served in the two-hop cooperative phase.

An expression for $P_{\text{th}}$, conditioned on $K_{2h} = N$ can be written as follows in (9) at the bottom of the page. For a practical wireless network in which the channel fading distribution depends on path-loss and shadowing, the evaluation of (9) is challenging. Simplification of (9) can be obtained in the following special case. Let’s assume a setup with fixed nominal SNR $\rho$ on all AP-device and device-device links with i.i.d. small-scale fading $h$. In such a scenario, using (1), the probability of decoding failure with $m$ cooperating transmitters at rate $R$ is as follows.

$$ p(m, R) = \Pr \left( W \log \left( 1 + \rho \sum_{i=1}^m |h_i|^2 \right) < R \right), $$

(10)

where $h_j \sim CN(0,1)$, are i.i.d. random variables. Therefore, $\sum_{m=1}^m |h_i|^2$ has the Erlang distribution and $p(m)$ can be computed as

$$ p(m) = \gamma \left( m, \frac{\omega}{F_1} \right), $$

(11)

where $\gamma(x, y) = \int_0^x t^{y-1} e^{-t} dt$ is the incomplete Gamma function. Moreover, $\omega = W \cdot \sigma_0 \cdot (2^{R/w} - 1)$ and $\sigma_0$ denotes PSD of the AWGN and $P_1$ denotes the transmit power at each transmitting node.

In such simplified scenario, as similarly suggested in [10], [9] can be reformulated as follows.

$$ P_{\text{th}}(D) = \sum_{n=0}^{N-1} \left( q_b^M \right)^{N-n} \left( 1 - q_b^M \right)^n \left( 1 - \left( 1 - q_r(M+n) \right)^{N-n} \right), $$

(12)

where $q_b^M = p(M, R_{2h,b})$ and $q_r(M+n) = \min\{1, p(M+n, R_{2h,r})/p(M, R_{2h,b})\}$,

(13)

is the conditional failure probability of a device in relaying hop given that it failed in broadcast hop.

D. Diversity-Multiplexing Tradeoff Analysis

In this section, we analyze the diversity-multiplexing tradeoff of the proposed scheme for the case of P-CSI, assuming independent Rayleigh distributed fading for all links, using the definition in (3). First, note that when transmit power goes to infinity, the achievable transmission rate from (3) also approaches infinity, resulting in $D_{1h} = D$, when $0 < \beta \leq 1$. Therefore, unless $\beta = 0$, all the devices are scheduled in the single-hop rate-adaptive phase. For that reason, we analyze the diversity-
multiplexing tradeoff for two extreme cases of $\beta = 1$ and $\beta = 0$, respectively, when all the devices are scheduled in single-hop rate-adaptive phase and, when all the devices are scheduled in two-hop cooperative phase. This also provides lower bounds for the diversity-multiplexing tradeoff of the proposed ANDCoop scheme.

**Proposition 2.** When all the devices are scheduled in single-hop rate-adaptive phase, the diversity order of the considered system at zero multiplexing is given by

$$d_{\text{single-hop}}(0) = M. \quad (14)$$

**Proof.** See Appendix [B]

Moreover, following the proof in Appendix [B] upper and lower bounds of the diversity-multiplexing tradeoff are readily derived as follows for the case where all the devices are scheduled over single-hop transmission.

$$M(1 - r) \leq d_{\text{single-hop}}(r) \leq M(1 - \frac{r}{N}). \quad (15)$$

For the case when all the devices are scheduled in two-hop cooperative phase (i.e., the OccupyCoW protocol in [10]), the following proposition presents the diversity-multiplexing tradeoff for the general case of $0 < \alpha < 1$, when $M > 1$.

**Proposition 3.** When all the devices are scheduled in two-hop cooperative phase, the diversity-multiplexing tradeoff is given by

$$d_{\text{two-hop}}(r) = (M + N - 1) \left(1 - \frac{r}{1 - \alpha}\right), \quad (16)$$

where at zero multiplexing gain it yields

$$d_{\text{two-hop}}(0) = M + N - 1. \quad (17)$$

**Proof.** See Appendix [C]

Intuitively, diversity order $M + N - 1$, i.e., the slope of outage probability curve in high SNR, corresponds to the case when all the $M$ APs cooperate with $N - 1$ strongest devices to transmit to the weakest device. It is an interesting observation from (16) that the tradeoff between diversity order $d$ and multiplexing gain $r$ in high SNR is controlled by the inverse of $1 - \alpha$. In other words, the duration of the relaying phase, which directly affects the outage probability for the weakest devices, controls the diversity-multiplexing tradeoff in high SNR. Therefore, for a given multiplexing gain $r$, the maximum diversity is achieved when $\alpha$ is the minimum allowed value for (16) to be non-negative, i.e., $0 < \alpha \leq 1 - r$. Since $\alpha$ cannot be zero in (16), the following upper bound is valid for the two-hop transmission for $r > 0$.

$$d_{\text{two-hop}}(r) < (M + N - 1)(1 - r). \quad (18)$$

This upper bound is depicted by the dashed green line in Fig. 4. For the case of $\alpha = \frac{1}{2}$, which is the exercised design in [10], [52], [53], the diversity-multiplexing tradeoff in (16) becomes

$$d_{\text{two-hop}}(r)|_{\alpha=1/2} = (M + N - 1)(1 - 0.5 \cdot r) \quad (19)$$

As also depicted in Fig. 4, in such case the maximum achievable multiplexing gain is $r = 0.5$, intuitively corresponding to the fact that each message is transmitted twice with the same rate, once in broadcast phase and once more in the relaying phase.

It is clear that the two-hop operation in (19) is spectrally inefficient, due to the fact that at very low system outage probability the gain from cooperative relaying is small, thus only a small percentage of the devices will benefit from relaying. On the other hand, the single-hop transmission from Proposition 2 can achieve higher multiplexing gain than (19). This further suggests that it is best to capture the relaying benefit only for that small percentage of the devices that experience a weak channel to the APs, while enjoying the high rate single-hop transmission to the devices with strong channel, which in turn increases the overall spectral efficiency. Moreover, note that since by design the outage probability of the proposed ANDCoop scheme is upper bounded by that of the two extremes studied in Proposition 2 and Proposition 3 then from (2) we readily have $d_{\text{single-hop}}(r) \leq d_{\text{ANDCoop}}(r)$ and $d_{\text{two-hop}}(r) \leq d_{\text{ANDCoop}}(r)$ for given $\alpha$ and $r$.

**IV. Numerical Results**

This section presents numerical results from simulating DL operation of the network described in Section III where $M$ single-antenna APs and $N$ single-antenna devices are randomly distributed across the factory area. To this end, we start by analyzing the performance with the assumption of P-CSI, to focus on system parameter designs. Then, we extend the analysis to the case of 1-CSI, and study the impact of CSI estimation error on the performance indicators.

The plots presented throughout this section are generated using a system-level simulation, where we adopt the parameters summarized in Table II (except in cases where stated otherwise). Path loss exponents are determined using the factory and open-plan building channel model in [20]. The probability that a link is LOS is derived based on the distance of the communicating nodes, $\nu$, using the following function.

$$p_L(\nu) = a + \nu_{\leq b} \frac{1 - a}{b^2} (\nu - b)^2, \quad (20)$$
further relaxes the assumption of tight synchronization among antennas for distributed cooperative transmission. 

joint transmission and beam-forming at the transmitter. This differentiates our work from CSI-based distributed multi-user systems, such as in [42], which rely on coherent knowledge of the channel gains for all the AP-device links. We emphasize that in the present work, the CSI is solely used for the purpose of transmission rate adaptation, meaning that the channel coefficient phase is not collected nor utilized. This differentiates our work from CSI-based distributed multi-antenna systems, such as in [42], which rely on coherent joint transmission and beam-forming at the transmitter. This further relaxes the assumption of tight synchronization among antennas for distributed cooperative transmission.

A. Performance Analysis with Perfect CSI

Let’s start by assuming that the controller has perfect knowledge of the channel gains for all the AP-device links. We emphasize that in the present work, the CSI is solely used for the purpose of transmission rate adaptation, meaning that the channel coefficient phase is not collected nor utilized. This differentiates our work from CSI-based distributed multi-antenna systems, such as in [42], which rely on coherent joint transmission and beam-forming at the transmitter. This further relaxes the assumption of tight synchronization among antennas for distributed cooperative transmission.

Table II: Simulation parameters setup.

| Parameter description | Value |
|-----------------------|-------|
| Floor area            | $100 \times 100$ m$^2$ |
| Number of devices, $N$| 50    |
| Number of APs, $M$    | 1, 2 or 3 |
| Data per device       | 50 Bytes |
| Cycle duration, $T$   | 1 ms  |
| Bandwidth             | 20 MHz |
| Carrier frequency     | 3.5 GHz ($\lambda \approx 8.57$ cm) |
| AP transmit power, $P_a$| 23 dBm |
| device transmit power, $P_d$| 23 dBm |
| PSD of the AWGN       | -174 dBm/Hz |
| Path loss exponent ($\nu \leq 10\lambda$) | 2 |
| LOS path loss exponent ($\nu > 10\lambda$) | 3.26 |
| NLOS path loss exponent ($\nu > 10\lambda$) | 3.93 |
| Blockage model: probability parameter $a$ | 0.25 |
| Blockage model: cutoff parameter $b$ | 15 m |
| Shadowing power value: |
| LOS, from AP antenna  | 1.4 dB |
| NLOS, from AP antenna | 4.6 dB |
| LOS, from device antenna | 8.7 dB |
| NLOS, from device antenna | 15.2 dB |

where $a$ is a fixed probability mass, and $b$ is the cutoff above which the probability of a link being LOS becomes fixed to $a$. The link is therefore non-line-of-sight (NLOS) with probability of $1 - p_L(\nu)$. The cycle duration, number of devices, data per device and bandwidth are given values similar to those in [10] and [5].

With respect to the optimization of $\beta$, the following schemes are studied in this section.

- $\beta = \hat{\beta}$: This represents our proposed ANDCoop scheme, where an optimal $\hat{\beta}$ portion of the total time is allocated for rate-adaptive single-hop transmission to a subset of the devices with the highest instantaneous channel quality. The remaining $1 - \hat{\beta}$ portion of the time is then used for two-hop transmission to the remaining devices.
- $\beta = 1$, ideal rate adaptation: This transmission scheme mimics the typical transmission in cellular technologies, such as LTE, where, the transmission rate for each user is adapted to the instantaneous channel quality.
- $\beta = 0$, two-hop transmission: This is a special case of our proposed scheme, where the total time resources is allocated to the two-hop transmission towards all the users. The scheme was originally proposed in [10] and is known as the OccupyCoW protocol.

Proposed scheme improves spectral efficiency: In Fig. 5 system outage probability is shown against spectral efficiency $\eta$, derived as $\eta = \frac{M}{K}$. The proposed ANDCoop scheme with optimized time division of $\beta = \hat{\beta}$, improves spectral efficiency by at least 0.5 bpcu when $M = 1$ AP is deployed. The gain is higher when a larger number of APs are deployed. Namely, with $M = 2$ and $M = 3$, more than 1 and 1.5 bpcu increase in spectral efficiency is achieved with respect to the case of $\beta = 0$, i.e., when only two-hop cooperative transmission is deployed.

The gain in spectral efficiency is thanks to transmitting packets to strong devices with high rate in the single-hop phase, allowing the two-hop phase to accommodate the weak devices reliably at even large packet sizes. This way, the robustness of rate-adaptation to increase in load is combined together with the robustness of OccupyCoW to fading, providing an improved reliability at a higher spectral efficiency. Fig. 6 shows the cumulative density function (cdf) of the
number of weak devices scheduled with two-hop transmission by the proposed ANDCoop scheme with optimized $\beta$. The statistics are collected for the points in Fig. 5 where the proposed ANDCoop achieves $P_{out} = 10^{-5}$. Interestingly, the average number of users scheduled with two-hop transmission is just below 13, 7 and 3 respectively for the case of 1, 2 and 3 APs.

**Ultra-reliability at lower transmit power:** By fully exploiting the diversity gain in the network, the proposed ANDCoop scheme relaxes the need for high SNR to achieve ultra-reliability. As it is shown in Fig. 7, system outage probability of $P_{out} = 10^{-5}$, the required transmit power of the proposed scheme reduces by a few dB compared to the OccupyCoW protocol. Such transmit power gap, when compared against the case of single-hop with ideal rate adaptation, can grow to tens of dB. Aside from improving the overall energy efficiency of the system, operating at a lower transmit power can also reduce the interference generated by the cell towards neighboring cells, in case of a multi-cell operation, as also studied in [32]. Moreover, the proposed ANDCoop can naturally reduce the average relaying time per relay device, by reducing the overall duration of the relaying phase. The combined effect is a significant reduction in the average consumed energy in the relaying phase across devices, as depicted in Fig. 8. The curves suggest 30% to 40% reduction in average relaying energy consumption in all cases.

**Quick reach to the maximum diversity gain:** We study the empirical outage exponent of the proposed transmission scheme in Fig. 9. For that purpose, we adopt a simulation setup where all links exhibit a single nominal average SNR value, i.e., removing the effect of large-scale fading in channel gain. The system outage probability is then simulated across a finite range of link SNR. As depicted in Fig. 9 with optimal $\beta = \hat{\beta}$, the proposed protocol reaches quickly to the maximum achievable diversity order of $M + N - 1$ at $M = 3$, confirming the derivation in (17). This is thanks to collecting the multi-user diversity gain at its best, by rate-adaptive scheduling of the devices with strong channel condition, while exploiting the spatial diversity gain from cooperative relaying towards the devices with poor channel condition. Interestingly, with $\beta = 1$, the gain from multi-user diversity can initially increase the outage exponent. By increasing SNR, where all devices will naturally be scheduled with the same transmission rate, the diversity order approaches to $M$, as was also suggested by the derivation in (14).

**Improved scalability with network size:** In practical industrial networks, the number of devices connected to the same controller can become largely dynamic. Therefore, it is crucial for the transmission protocol to be able to scale with the network size, up or down, without depriving it of reliability. To that end, in Fig. 10 the system outage probability of the three transmission schemes are tested against a range of network sizes, i.e., the number of devices in the network, $N$. We fixed the packet size for each device to $B = 50$ bytes to imitate the realistic conditions.
The system outage probability for the case of single-hop transmission with ideal rate adaptation increases, almost linearly, by increasing the network size. This is an expected outcome since the system is unable to gain from the increase in number of devices (maximum diversity order or M, as proposed in (14)). Thus, increasing the number of devices, merely translates into a higher likelihood of scheduling time-overflow.

On the contrary, the proposed ANDCoop protocol and the OccupyCoW protocol can benefit from the increase in network device. In fact, by increasing the network size, the potential cooperative diversity gain also increases, which in turn reduces the system outage probability. Meanwhile, by increasing the network size, the average transmission rate increases too, which has an opposite effect on outage probability. Therefore, for those two schemes, we observe a turning point for system outage probability. Overall, the proposed ANDCoop can guarantee $P_{out} \leq 10^{-5}$ for $N \leq 180$ with $M = 3$ APs in this example. For the OccupyCoW scheme this reduces to only $2 < N \leq 120$. It should be noted that at $N = 1$, the proposed scheme is equivalent to single-hop transmission since the total resources are allotted to the single device. Moreover, the overall scheduling overhead also increases with the number of devices increasing. However, since a fixed packet size per device is assumed in this analysis, by introducing a fixed scheduling overhead per device, the trend of the curves in Fig. 10 and the above conclusions will remain intact.

**B. Effect of Imperfect CSI**

As discussed earlier in Section III-A, due to the inevitable CSI estimation error, the transmitter must use a back-off parameter $0 < \theta \leq 1$ to adjust the transmission rate that is adapted to the I-CSI. Moreover, the effect of I-CSI is only on the single-hop rate-adaptive transmission phase. The two-hop phase, thanks to the fixed-rate transmission, encounters no impact from the I-CSI.

Numerical optimization in presence of CSI error is a demanding task which requires exhaustive search for the optimal operating point across three parameters $L$, $\beta$ and $\theta$. Therefore, it is crucial to understand the impact that each of those parameters have on the performance in order to reduce the optimization complexity.

**Fixing a small number of pilot symbols per device:** To reduce the complexity of the exhaustive numerical optimization we restrict each of the three parameters $L$, $\beta$ and $\theta$, to a finite set of values. Then, for each triple, we simulate the system outage probability. The curves depicted against parameter $L$ in Fig. 11 show the course of system outage probability across different values of $\theta$ when we fixed $\beta = 0.1$. Similarly, in Fig. 12 system outage probability is depicted for different $\beta$ values while fixing $\theta = 0.6$. The best case system outage probability in both those figures, represents the minimum outage probability that is attainable at a given $L$.
while optimizing against $\beta$ and $\theta$. The following observations are given.

- By increasing $L$, channel estimation error decreases, which in turn lowers the impact of $\theta$ on system outage probability for fixed $\beta$.
- By optimization across different values of $\beta$ and $\theta$, it becomes evident that system outage probability is within a small margin of the optimal value, across a wide range of $L$. In this example, choosing $2 \leq L \leq 30$, system outage probability remains roughly unchanged.

From those observations, to simplify the optimization process we propose to fix $L = 10$ and optimize only across $\beta$ and $\theta$.

**Impact of channel estimation error is marginal:** For fixed number of pilot symbols per device $L = 10$, we examine the performance degradation of the proposed ANDCoop from I-CSI with respect to the case of P-CSI under similar setup as in Fig. 7. As shown, for both cases of $M = 1$ and $M = 3$, in presence of I-CSI the proposed scheme with $\beta = \hat{\beta}$ operates within a small 1-2 dB gap from the case of P-CSI. On the other hand, the gap for the case of single-hop rate-adaptive transmission can become very large, e.g., 15 dB for the case of $M = 3$. Such large SNR gap owes to high channel estimation error of the devices with poor channel quality during rate adaptation for single-hop transmission. Our proposed ANDCoop circumvents that by identifying those devices and scheduling them over fixed-rate two-hop transmission.

**Optimal value for $\beta$ and $\theta$ for fixed $L$:** In Fig. 14 the optimal values $\hat{\beta}$ and $\hat{\theta}$ are reported for fixed $L = 10$. Those values were used in Fig. 13 for the proposed ANDCoop in case of I-CSI. It is evident that with a larger number of AP antennas, on average a larger number of devices are scheduled with single-hop transmission (i.e., larger $\hat{\beta}$). Moreover, the optimal rate adjustment factor $\hat{\theta}$ is smaller, when the number of AP antennas is smaller. As could be expected, both $\hat{\beta}$ and $\hat{\theta}$ have a non-increasing trend with system outage probability decreasing. This parallels our design analogy for ultra-reliable communication, where only the devices with strong channel conditions should undergo rate-adaptive transmission (i.e., smaller $\beta$), and for those, a more conservative transmission rate adjustment factor is necessary (i.e., smaller $\theta$).

V. CONCLUSION

We proposed a channel-aware URLLC transmission protocol for industrial wireless control where a controller communicates with several devices in the DL. The proposed transmission protocol uses the knowledge of instantaneous channel conditions of AP-device links to identify devices with strong and weak channel conditions. The strong devices are served with a single-hop rate-adaptive transmission where the rate is adapted to the instantaneous channel. With this approach, multi-user diversity gain is exploited and frequency resources are efficiently utilized. Meanwhile, the weak devices enjoy a two-hop cooperative communication in which transmission rate is fixed and all the nodes in the network cooperate in relaying. We analyzed the system outage probability and the diversity order under the proposed transmission protocol. Through numerical analysis we derived optimal time division between the two sets of strong and weak devices and showed that such optimization can improve spectral efficiency by more than 0.5, 1 and 1.5 bpcu, when the controller is equipped with 1, 2 and 3 AP antennas, respectively. Moreover, we observed that the proposed ANDCoop transmission protocol can effectively reduce the required transmit power for reliable industrial wireless control, improve the scalability with respect to network size, and marginalize the impact of channel estimation error on outage probability. The improvements are thanks to the instantaneous awareness to channel conditions that allows to exploit different sources of diversity gain in the network. As the continuation of this work in future, we will look into evaluating the performance of the proposed transmission protocol considering spatio-temporal correlation of shadowing caused by blockages. Further, we will study
the use of dedicated full-duplex relay nodes in the proposed transmission protocol.

APPENDIX

A. Proof of Proposition 1

The achievable rate $c_j$ for device $j$ is given as

$$c_j = W \log \left( 1 + \sum_{i \in A} g_{i,j}^{\alpha_i} \right), \quad (21)$$

measured in bps. Then, the random time duration $\tau_j$, in seconds, required for successful transmission to device $j$ is equal to $\tau_j = \frac{B'}{c_j}$, where $B' = \frac{N}{KT}$ is the adjusted packet size per scheduled device for a given $K$. Note that $c_j$’s are i.i.d. random variables which result in i.i.d. $\tau_j$’s. The transmission from source to $K$ arbitrarily chosen devices is then successful if the sum of $\tau_j$’s for those $K$ devices is not larger than $T$. Without loss of generality, let’s assume $\tau_1 \leq \tau_2 \leq \ldots \leq \tau_N$, meaning that $c_1 \geq c_2 \geq \ldots \geq c_N$, where $c_j$’s form order statistics drawn from cdf $F_c$.

For the sake of better reliability (i.e., maximum diversity gain), the scheduler chooses the $K$ devices with best channels to transmit to, where $K \in \{1, 2, \ldots, N\}$. Thus, the probability of transmission error is equivalent to the probability of time overflow given as

$$P_{\text{out}} = \Pr \left( \sum_{j=1}^{K} \tau_j > T \right) = \Pr \left( \sum_{j=1}^{K} \frac{1}{c_j} \geq \frac{KT}{NB} \right). \quad (22)$$

The diversity gain $d$ from (22) can be derived for the case of i.i.d. Rayleigh fading for all links and fixed average SNR of $\rho$ over all links, as follows. First, note that

$$\Pr \left( \frac{1}{c_j} \geq \frac{1}{R} \right) = \sum_{k=K-j+1}^{N} \binom{N}{k} F_c(R)^k (1 - F_c(R))^{N-k} \quad (23)$$

or

$$= \sum_{k=K-j+1}^{N} \binom{N}{k} p(M,R) p(M,R)^{N-k}, \quad (24)$$

where (a) follows from the cdf of the $N-j+1$th order statistics [43 Chapter 6] and (b) follows from (10). Using the approximations $p(m,R) \approx \left( \frac{\omega}{R} \right)^m$ and $(1 - p(m,R)) \approx 1$ for $\frac{\omega}{R} \to 0$ [41], the following holds for any bounded real value $R$.

$$d_j = -\lim_{R \to \infty} \frac{\log \Pr \left( \frac{1}{c_j} \geq \frac{1}{R} \right)}{\log P_t} = -\lim_{R \to \infty} \frac{\log \sum_{k=N-j+1}^{N} \binom{N}{k} \left( \frac{\omega}{R} \right)^k}{\log P_t} = M(N-j+1) \quad (24)$$

For the case where $K = 1$ device with the best channels is transmitted to, the diversity gain follows from (24) as

$$d = MN. \quad (25)$$

For $K > 1$, the maximum diversity gain follows from the choice of $K$ devices with best channels where the probability of outage $P_{\text{out}}$ from (22) is bounded as follows

$$\Pr \left( \frac{1}{c_K} \geq \frac{KT}{NB} \right) \leq \Pr \left( \sum_{j=1}^{K} \frac{1}{c_j} \geq \frac{KT}{NB} \right) \leq \Pr \left( \frac{1}{c_K} \geq \frac{T}{NB} \right).$$

Therefore, the diversity order of $P_{\text{out}}$ is bounded on both sides by $M(N-K+1)$ according to (24), which concludes

$$d = M(N-K+1). \quad (26)$$

B. Proof of Proposition 2

Although a closed form of outage probability in (7) is not available, the outage probability $P_{\text{out}} = \Pr_{i}(T_{\text{th}})$ is bounded as follows.

$$1 - \left( 1 - p \left( M, \frac{B}{T_{\text{th}}} \right) \right)^N \leq P_{\text{out}} \leq 1 - \left( 1 - p \left( M, \frac{NB}{T_{\text{th}}} \right) \right)^N \quad (27)$$

The upper bound in (27) is realized by dividing the time $T_{\text{th}}$ equally among the devices, while the lower bound is realized by allotting the time $T_{\text{th}}$ to every device. Therefore, denoting the diversity order of the upper and the lower bounds in (27), respectively, by $d_{\text{upper}}$ and $d_{\text{lower}}$, it can be concluded from (2) that

$$d_{\text{upper}} \leq d \leq d_{\text{lower}}. \quad (28)$$

Using the approximation $p(m,R) \approx \left( \frac{\omega}{R} \right)^m$ for $\frac{\omega}{R} \to 0$ [41], the following holds for any bounded real value $R$.

$$-\lim_{R \to \infty} \frac{\log 1 - (1 - p(M,R))^N}{\log P_t} = -\lim_{R \to \infty} \frac{\log N \left( \frac{\omega}{R} \right)^M}{\log P_t} = M$$

Therefore, we have $d_{\text{upper}} = d_{\text{lower}} = M$, which according to (28) yields (14).

C. Proof of Proposition 3

We start from the probability of outage $P_{\text{out}} = \Pr_{2h}(D)$ in (12). First note that for $P_t \to \infty$, where $n > 0$ we have

$$\frac{p(M+n, R_{2h,h})}{p(M, R_{2h,h})} = \left( \frac{\omega_{2h,h}}{R_t} \right)^{M+n}, \quad (29)$$

where $\omega_{2h,h} = W \cdot \sigma_0 \cdot (2R_{2h,h}/W - 1)$, and $\omega_{2h,r} = W \cdot \sigma_0 \cdot (2R_{2h,h}/W - 1)$, and

$$R_{2h,h} = \frac{NB}{\alpha T} = \frac{W \log P_t}{\alpha}, \quad (30)$$

$$R_{2h,r} = \frac{NB}{(1-\alpha)T} = \frac{W \log P_t}{1-\alpha}. \quad (31)$$

For the case where $n = 0$ and $\alpha \geq 0.5$, we have $q_r^{(M+n)} = 1$. Otherwise, $q_r^{(M+n)}$ is derived using (29). Therefore, in the limit of $P_t \to \infty$, we use the following approximation,

$$1 - \left( 1 - q_r^{(M+n)} \right)^{(N-n)} \approx \begin{cases} 1 & n = 0 \text{ & } \alpha \geq 0.5 \\ (N-n)q_r^{(M+n)} & \text{otherwise} \end{cases} \quad (32)$$
We further use the approximation \( (1 - q_b^M)^n \approx 1 \) in high SNR. Thus, we obtain

\[
P_{\text{out}} \approx \sum_{n=0}^{N-1} \left( q_b^M \right)^{(N-n)} \left( 1 - \left( 1 - (q_b^M(q_n^r))^{(N-n)} \right) \right).
\]

(33)

Using the approximation in (32) it easily follows that for \( M > 1 \), the slowest term in (33) approaching zero as \( P_t \to \infty \) is the term of \( n = N - 1 \). Therefore, we use this term to approximate \( P_{\text{out}} \), where substituting in (4) yields (16).

REFERENCES

[1] G. Cena, A. Valenzano, and S. Vitturi, “Hybrid wired/wireless networks for real-time communications,” IEEE Ind. Electron. Mag., vol. 2, no. 1, pp. 8–20, Mar. 2008.

[2] M. Bennis, M. Debub, and H. V. Poor, “Unreliable and low-latency wireless communication: Tail, risk, and scale,” Proceedings of the IEEE, vol. 106, no. 10, pp. 1834–1853, Oct. 2018.

[3] H. Viswanathan and P. E. Mogensen, “Communications in the 6G era,” IEEE Access, vol. 8, pp. 50663–50704, 2020.

[4] V. C. Gungor and G. P. Hancke, “Industrial wireless sensor networks: Challenges, design principles, and technical approaches,” IEEE Trans. Ind. Electron., vol. 56, no. 10, pp. 4256–4265, Oct. 2009.

[5] M. Weiner, M. Jorgovanovic, A. Sahai, and B. Nikolic, “Design of a low-latency, high-reliability wireless communication system for control applications,” in IEEE Intl. Conf. on Commun. (ICC’14), June 2014, pp. 3829–3835.

[6] G. Berardini, N. H. Mahmood, I. Rodriguez, and P. Mogensen, “Beyond 5G wireless IRT for Industry 4.0: Design principles and spectrum aspects,” in IEEE Global Commun. Conf. (GLOBECOM’18), Dec. 2018, pp. 1–6.

[7] J. Mazgula, J. Sapis, U. S. Hashmi, and H. Viswanathan, “Ultra reliable low latency communications in mmWave for factory floor automation,” Journal of the Indian Institute of Science, pp. 1–12, 2020.

[8] J. Park, S. Samarakoon, H. Shiri, M. K. Abdel-Aziz, T. Nishio, A. El-gabli, and M. Bennis, “Extreme urllc: Vision, challenges, and key enablers,” arXiv preprint arXiv:2001.09683, 2020.

[9] P. Zand, S. Chatterjee, K. Das, and P. Havinga, “Wireless industrial monitoring and control networks: The journey so far and the road ahead,” Journal of sensor and actuator networks, vol. 1, no. 2, pp. 123–152, 2012.

[10] V. N. Swamy, S. Suri, P. Rigge, M. Ganade, A. Sahai, and B. Nikolic, “Cooperative communication for high-reliability low-latency wireless control,” in IEEE Intl. Conf. on Commun. (ICC’15), June 2015, pp. 1193–1198.

[11] R. Candell, K. A. Remley, J. T. Quimby, D. Novotny, A. Curtin, P. B. Papazian, M. Kashef, and J. Diener, “Industrial wireless systems radio propagation measurements,” National Institute of Standards and Tech., Tech. Rep. 1951, Jan. 2017.

[12] T. S. Rappaport, S. Y. Seidel, and K. Takamizawa, “Statistical channel impulse response models for factory and open plan building radio communication system design,” IEEE Trans. Commun., vol. 59, no. 5, pp. 794–807, May 1991.

[13] Y. Polyanisky, H. V. Poor, and S. Verdú, “Channel coding rate in the finite blocklength regime,” IEEE Trans. Inf. Theory, vol. 56, no. 5, pp. 2307–2359, May 2010.

[14] W. Yang, G. Durisi, T. Koch, and Y. Polyanisky, “Quasi-static multiple-antenna fading channels at finite blocklength,” IEEE Trans. Inf. Theory, vol. 60, no. 7, pp. 4232–4265, July 2014.

[15] R. Jurdi, S. R. Khosravirad, H. Viswanathan, J. G. Andrews, and R. W. Heath, “Outage of periodic downlink wireless networks with hard deadlines,” IEEE Trans. Commun., vol. 67, no. 2, pp. 1238–1253, Feb. 2019.

[16] S. R. Khosravirad and H. Viswanathan, “Adaptive network-device cooperative diversity for ultra-reliable and low-latency wireless control,” in IEEE Vehicular Technology Conference (VTC2019-Spring), Apr. 2019, pp. 1–6.

[17] “3GPP TR 38.913; study on scenarios and requirements for next generation access technologies,” 3GPP, Tech. Rep., 2017.

[18] L. Zhao, W. Mo, Y. Ma, and Z. Wang, “Diversity and multiplexing tradeoff in general fading channels,” IEEE Trans. Inf. Theory, vol. 53, no. 4, pp. 1549–1557, Apr. 2007.

[19] L. Zheng and D. N. C. Tse, “Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels,” IEEE Trans. Inf. Theory, vol. 49, no. 5, pp. 1073–1096, May 2003.

[20] T. Yoo and A. Goldsmith, “Capacity and power allocation for fading MIMO channels with channel estimation error,” IEEE Trans. Inf. Theory, vol. 52, no. 5, pp. 2203–2214, May 2006.

[21] R. Knopp and P. A. Humblet, “Information capacity and power control in single-cell multiuser communications,” in IEEE Intl. Conf. on Commun. (ICC’95), vol. 1, June 1995, pp. 331–335 vol.1.

[22] M. Grossglauser and D. N. C. Tse, “Mobility increases the capacity of ad hoc wireless networks,” IEEE/ACM Trans. on Netw., vol. 10, no. 4, pp. 477–486, Aug. 2002.

[23] V. N. Swamy, P. Rigge, G. Ranade, B. Nikolic, and A. Sahai, “Wireless channel dynamics and robustness for ultra-reliable low-latency communications,” IEEE J. Sel. Areas Commun., vol. 37, no. 4, pp. 705–720, 2019.

[24] S. A. Ayoughi, W. Yu, S. R. Khosravirad, and H. Viswanathan, “Interference mitigation for ultra-reliable low-latency wireless communication,” IEEE J. Sel. Areas Commun., vol. 35, no. 2, pp. 302–316, May 2019.

[25] K. Shen, W. Yu, and S. R. Khosravirad, “Ultra-reliable wireless communication with message splitting,” in IEEE Intl. Workshop on Signal Process. Advances in Wireless Commun. (SPAWC), July 2019, pp. 1–5.

[26] B. M. Hochwald, T. L. Marzetta, and V. Tarokh, “Multiple-antenna channel hardening and its implications for rate feedback and scheduling,” IEEE Trans. Inf. Theory, vol. 50, no. 9, pp. 1893–1909, Sep. 2004.

[27] S. Kim, S. Kim, B. Lee, S. Ryu, H. Lee, and C. Cho, “Multi-hop relay based coverage extension in the IEEE802.16j based mobile WiMAX systems,” in Fourth Intl. Conf. on Networked Comput. and Adv. Inf. Manag., vol. 1, Sep. 2008, pp. 516–522.

[28] J. Gui and J. Deng, “Multi-hop relay-aided underlay D2D communications for improving cellular coverage quality,” IEEE Access, vol. 6, pp. 14318–14338, 2018.

[29] E. Lang, S. Redana, and B. Raaf, “Business impact of relay deployment for coverage extension in 3GPP LTE-Advanced,” in IEEE Intl. Conf. on Commun. (ICC’09), June 2009, pp. 1–5.

[30] D. Koziol, F. S. Moya, L. Yu, V. Van Phan, and S. Xu, “QoS and service continuity in 3GPP D2D for IoT and wearables,” in IEEE Conf. on Standards for Commun. and Netw. (CSCN), Sep. 2017, pp. 233–239.

[31] “3GPP TR 22.866; enhanced relays for energy efficiency and extensive coverage,” 3GPP, Tech. Rep., Feb. 2019.

[32] S. Singh, F. Ziliotto, U. Madhow, E. Belding, and M. Rodwell, “Blockage and directivity in 60 GHz wireless personal area networks: from cross-layer model to multihop MAC design,” IEEE J. Sel. Areas Commun., vol. 27, no. 8, pp. 1400–1413, Oct. 2009.

[33] J. N. Laneman, “Limiting analysis of outage probabilities for diversity schemes in fading channels,” in IEEE Global Telecom. Conf. (GLOBECOM’03), vol. 3, Dec. 2003, pp. 1242–1246.

[34] M. Alonzo, P. Baracca, S. R. Khosravirad, and S. Buzzi, “URLLC for factory automation: an extensive throughput-reliability analysis of D-
MIMO,” in 24th Intl. ITG Workshop on Smart Antennas (WSA’20), Feb. 2020, pp. 1–6.

[43] R. C. Mittelhammer, Mathematical Statistics for Economics and Business. Springer-Verlag New York, 1999.