A Power Efficient Cooperative Communication Protocol for 6G in-Factory Subnetworks

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***Abstract*—Industrial sixth generation (6G) wireless subnetworks are expected to support very short control communication cycles for multiple sensors. The achievement of demanding communication requirements in terms of latency and reliability might be challenged by signal fading and the presence of obstructors. In this paper, we propose a novel communication protocol for industrial subnetworks that leverages secondary access points (APs) acting as relays for improving the successful execution of short cycle times in a subnetwork, while reducing the overall emitted power. Our solution relies on a classification procedure for identifying the nodes to be served in relay mode, and an algorithm for minimizing the transmit power while coping with the timing constraints. Simulations results show the capability of the proposed approach of reducing the emitted power of up to 7.5 dB, while guaranteeing error probability and rate of resource overflow below 10^{-6}.**

***Index Terms*—In-X subnetworks, cooperative communication, decode and forward.**

I. INTRODUCTION

Industrial wireless networks are expected to support the needs of modern control systems, including cycle times in the order of $100\mu s$ and service availability exceeding five nines. These demanding prerequisites are beyond the capabilities of current 5G technology and call for a fundamental transformation in network infrastructure, where intelligence and decision-making capabilities are brought to the network edge [1], [2]. Short-range low power in-X subnetworks -to be installed in entities like robots and production modules for replacing the wired control infrastructure- are currently being studied by industry and academia in the context of 6G research with the aim of providing an efficient cost-effective wireless solution to the demands of industrial automation.

In spite of the short propagation range, blockage and signal fading due to e.g., metallic machineries, may hinder the possibility of achieving the demanding latency and reliability requirements. Relaying is widely recognized in the literature as an effective approach for mitigating fading by harnessing spatial diversity [3]. In particular, two-hop relaying protocols have been shown to substantially enhance both capacity and the quality of service (QoS) [4].

It is our hypothesis that the support of ultra-short communication cycle for in factory subnetworks requires the integration of link diversity to mitigate the impact of blockage effects. Several research works have explored the use of relays in the context of ultra-reliable low latency communication (URLLC) networks, see e.g., [3]–[7]. For instance, in [5], a wireless communication protocol tailored to industrial control systems is introduced. This protocol leverages cooperative transmission to assist nodes with poor channel conditions and utilizes direct transmission for stronger links. However, the criterion for selecting single-hop and two-hop devices is not explicitly presented. Moreover, relying on fixed power levels makes communication inefficient in terms of power emission. An algorithm for minimizing transmit power for cooperative communication in smart factories is instead introduced in [6]. This work focuses on throughput and reliability constraints only, disregarding the timing constraints introduced by the short control cycles. The work in [7] explores the application of unmanned aerial vehicles (UAVs) as decode-and-forward (DF) relays to facilitate the communication of short URLLC control packets between a controller and multiple mobile robots. The authors optimize the time-varying optimal blocklengths rather than the communication cycle time. Furthermore, the challenge of jointly managing relay selection and power control is examined in the context of vehicle platooning, where all users utilize a relay for transmission [8]. Similarly, the issue of relay selection is also considered for RF energy harvesting in [9].

While previous studies have focused on relay-assisted URLLC transmission, relay selection, and power control, there is a gap in the literature regarding an integrated approach to transmission protocol, relay selection, and power control tailored to the distinct needs of factory subnetworks. More specifically, they have not addressed the specific context of factory subnetworks, where minimizing power emissions is crucial for saving battery life and reducing interference with neighboring subnetworks [2].

In this paper, we propose a novel cooperative communication solution for industrial subnetworks aiming at improving the support of ultra-short communication with high reliability, while reducing the overall emitted transmit power. Our solution relies on the presence of secondary access points (sAPs) that forward the packet generated by a selected pool of sensors with disadvantageous propagation conditions to a primary AP (pAP), equipped with embedded controller capabilities. Specifically, our contribution is two-fold:

- We introduce a novel transmission protocol where sensors are scheduled into single-hop and two-hop transmission modes -with corresponding serving secondary AP- based on their channel state information (CSI), while coping with the tight timing constraint.
- We address the critical issue of minimizing the total transmit power while ensuring that the stringent cycle

time is met. To address the inherent non-convexity of the optimization problem, we employ a promising approach known as sequential parametric convex approximation (SPCA).

To the best of our knowledge, previous literature has not explored the integration of a transmission protocol with stringent time constraints, combined with the joint classification of devices and power minimization strategies, within factory subnetworks.

The remainder of this paper is structured as follows: Section II introduces the system model. Section III elaborates on the proposed communication protocol, while Section IV presents a detailed description of the steps involved in the proposed relay selection and power control algorithm. In Section V, simulation results are presented to validate the effectiveness of our approach. Finally, conclusions are summarized in Section VI.

II. SETTING UP THE SCENE

We consider an industrial subnetwork in which N sensors are wirelessly connected to $K+1$ APs. One of the APs acts as a primary AP (pAP), and has the capability of issuing control commands to the actuators, while the other K APs are secondary APs (sAPs), equipped with radio capabilities only. The set of all sAPs is denoted as $\mathcal{K}$, while $\mathcal{N}$ represents the set of all sensors in the subnetwork. Sensors can communicate directly with the pAP (single-hop direct transmission), or to both pAP and sAP. In the second case, the sAP will also forward the received message to the pAP, enabling a two-hop cooperative transmission. We denote as $\mathcal{N}_{1h}$ the set of devices scheduled for single-hop direct transmission, and as $\mathcal{N}_{2h}$ the set of devices scheduled for two-hop cooperative transmission.

Fig. 1 illustrates an example of a subnetwork with 5 sensors and 3 APs, where sensors A, B, C are scheduled in two-hop cooperative mode, while sensors D and E are scheduled in single-hop mode. Please note that in the case of sensors operating in cooperative mode, the pAP receives two copies of the transmitted packet - one via the cooperative link and the other via a direct link. This capability allows pAP to combine the energy received from the sensors in the first phase with that from sAP in the second phase.

This study assumes time-synchronized APs operating on a common frequency, using time division multiple access (TDMA) to assign time slots to sensors, avoiding intra-cell interference. It focuses on uplink (UL) transmissions, where sensors send packets of B_n bits to APs over W Hz bandwidth. All packets must be received by the primary AP within a T second time slot.

We assume that the pAP has an estimate of the channel responses of all communication links, i.e. between the sensors and the pAP/sAP, and between sAPs and pAP. This can be obtained in a training phase (as mentioned in [5]) via transmission of reference sequences. It is worth mentioning that channel responses are expected to be rather stable in a subnetwork, in the case of static sensors. It is therefore our assumption that, in a practical implementation, the training operation can be repeated at a relaxed temporization.

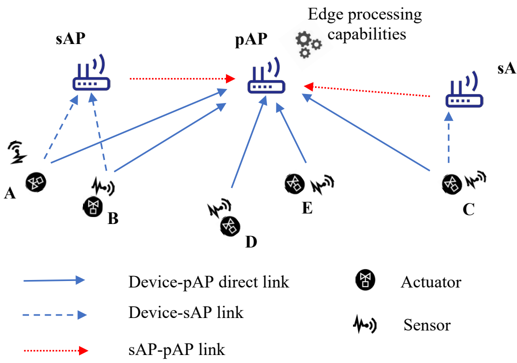

Fig. 1: System model for multiple APs subnetwork transmission.

The pAP scheduler uses the CSI of all subnetwork links for determining the subset of devices to be served in single-hop and two-hop transmission, as well as their transmission rate (and therefore the number of time resources) and transmit power by solving an optimization problem.

III. PROPOSED COMMUNICATION PROTOCOL

It is our assumption that communication reliability in a subnetwork can be enhanced by the presence of sAPs and their forwarding capabilities. Exploiting the presence of the sAPs requires a tailored communication protocol.

Our proposed protocol is illustrated in Fig. 2, along with a comparison with the basic TDMA protocol. The UL time slot is divided into three sub-slots of variable duration, corresponding to the first phase of the two-hop transmissions, the single-hop transmissions, and the second phase of the two-hop transmission. Sensors belonging to the $\mathcal{N}_{2h}$ set are then using the first phase sub-slot to transmit their packet, which is received by both the pAP and sAP. We assume that each sensor in $\mathcal{N}_{2h}$ is only served by the sAP for which it experiences the most advantageous channel conditions. The second phase sub-slot is used by the sAP for forwarding the received message from the sensors to the pAP. We assume here that the sAP acts as a DF relay. As mentioned above, the pAP can combine energy from the reception of the signal transmitted by sensors in $\mathcal{N}_{2h}$ during the first phase transmission with the energy received by the sAPs prior to decoding. Transmissions by sensors scheduled in the single hop sub-slot are instead only received by the pAP.

It is worth observing that, given the need of accommodating the two phases of the cooperative operation in the UL slot, transmission intervals of sensors in $\mathcal{N}_{2h}$ are necessarily shorter than in the basic TDMA protocol, and therefore a higher transmission rate is needed for transmitting their packet. In the following, we present the signal model of single-hop and two-hop DF relaying. Subsequently, the imperfect CSI (I-CSI) case will be considered. For the signal model, we consider the following notation. The vector of channel responses between the pAP and each of K sAPs is denoted by $\mathbf{h}_c \in \mathbb{C}^{K\times 1}$. The

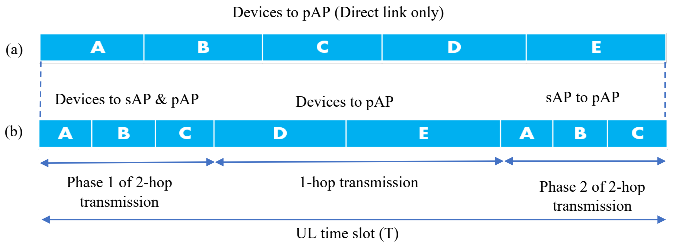

Fig. 2: (a) Basic TDMA protocol and (b) proposed cooperative protocol.

channel of pAP link to N devices is represented by $\mathbf{h}_p \in \mathbb{C}^{N\times 1}$. The channel matrix from N devices to K sAPs is $\mathbf{H}_s \in \mathbb{C}^{N\times K}$.

A. Signal model for single-hop transmission

Let us consider first perfect CSI (P-CSI) case, i.e. the pAP scheduler has a perfect knowledge of the channel responses of all the links for performing its decision. The Signal to Noise Ratio (SNR) of the nth device in the direct link to pAP is given by:

$$g_n^d = \frac{P_n|\mathbf{h}_p(n)|^2}{\sigma_0^2}, \quad \forall n \in \mathcal{N}_{1h} \tag{1}$$

where the superscript d stands for the direct link, σ_0 is the standard deviation of the noise, and P_n is the transmit power of device n. The achievable information rate of the nth device in the direct link to pAP can be written as:

$$r_n^d = \log_2\left(1 + g_n^d\right), \quad \forall n \in \mathcal{N}_{1h} \tag{2}$$

Assuming time division multiplexing only over a bandwidth W, a packet of B_n bits for the nth device can be transmitted in a time $t_n^d = \frac{B_n}{Wr_n^d}$. The packets of all single-hop devices can be then transmitted in a TDMA fashion resulting in a total transmission time:

$$T_{1h} = \sum_{n\in\mathcal{N}_{1h}} t_n^d \tag{3}$$

B. Signal Model for DF relaying

In the cooperative link model, each device's transmission is initially received by an sAP, then decoded and forwarded to the pAP. We introduce a relaying strategy that assigns the strongest sAP to each device, known as the '1 of K' relaying method. This approach provides a flexible way to improve communication reliability and coverage. The strongest sAP for the nth device is denoted by D_n, with $D_n \in \mathcal{D} \subseteq \mathcal{K}$. The SNR and the achievable rate for the nth device at the D_nth sAP are specified respectively.

$$g_{n,D_n} = \frac{P_n|\mathbf{H}_s(n,D_n)|^2}{\sigma_0^2}, \quad \forall n \in \mathcal{N}_{2h},\ \forall D_n \in \mathcal{K} \tag{4}$$

$$r_{n,D_n}^{(1)} = \log_2\left(1 + g_{n,D_n}\right), \quad \forall n \in \mathcal{N}_{2h},\ \forall D_n \in \mathcal{K} \tag{5}$$

where the superscript (1) indicates the first phase in the two-hop cooperative transmission. Assuming that the sAP re-encodes and transmits the received signal to pAP, the SNR and the achievable rate from the D_nth sAP to the pAP are respectively given by:

$$g_{D_n,p} = \frac{P_{D_n}^s|\mathbf{h}_c(D_n)|^2}{\sigma_0^2}, \ \forall n \in \mathcal{N}_{2h},\ \forall D_n \in \mathcal{K}, \tag{6}$$

$$r_n^{(2)} = \log_2\left(1 + g_{D_n,p} + g_n^d\right), \ \forall n \in \mathcal{N}_{2h},\ \forall D_n \in \mathcal{K}, \tag{7}$$

where the subscript p and the superscript (2) indicate the pAP and the second phase in the two-hop cooperative transmission, respectively. Additionally, $P_{D_n}^s$ represents the transmit power of the D_nth sAP. It is worth noting that (7) considers energy combining of the two transmission phases at the pAP receiver. In order to perform DF, the signal transmitted by device n has to be correctly decoded by the strongest sAP, and re-encoded in a new message. The amount of over-the-air time needed for successfully transmitting a packet of B_n bits by device n is then given by:

$$t_n^{(2h)} = \frac{B_n}{Wr_{n,D_n}^{(1)}} + \frac{B_n}{Wr_n^{(2)}}, \ \forall n \in \mathcal{N}_{2h}, \tag{8}$$

We denote respectively the total time of transmission for all devices in the first and second phase of two-hop method as:

$$T_{2h}^{(1)} = \sum_{n\in\mathcal{N}_{2h}} \frac{B_n}{Wr_{n,D_n}^{(1)}}, \tag{9}$$

$$T_{2h}^{(2)} = \sum_{n\in\mathcal{N}_{2h}} \frac{B_n}{Wr_n^{(2)}}, \tag{10}$$

The total time of transmission in both single-hop and two-hop cases is then calculated as:

$$T^{DF} = T_{1h} + T_{2h}^{(1)} + T_{2h}^{(2)}, \tag{11}$$

Every device expects an independent B_n bits of data to be delivered in T seconds over a bandwidth of W Hz. The total transmission time must not exceed the predefined time T, i.e., $T^{DF} \leq T$. Otherwise, a time overflow occurs. We utilize the *overflow rate* to quantify the occurrence of events where $T^{DF} > T$. Note that time overflow is the only source of errors in the P-CSI case.

C. I-CSI

We consider now the case of imperfect CSI (I-CSI), where channel responses are estimated by using the pilot training sequence for each device. Let us assume that we use L training symbols for each device with duration of $T_p = LT_s$ where $T_s = 1/W$ is the symbol period. The pilot training time for the all devices must then be subtracted from the given uplink time, i.e. $T_U \triangleq T - NLT_s$. Assuming that recursive minimum mean-square-error (MMSE) channel estimation is used, the true Rayleigh fading channel gain g can be written as $g = \hat{g} + \epsilon$, where $\epsilon \sim \mathcal{CN}(0, \sigma_e(L))$, $\hat{g} \sim \mathcal{CN}(0, 1 - \sigma_e(L))$, [5] and

$$\sigma_e(L) = \frac{1}{1 + L \cdot \mathrm{SNR}} \tag{12}$$

where $\sigma_e(L)$ denotes the variance of the channel estimation error [5]. To mitigate the impact of outage errors resulting from inaccuracies in channel estimation, the transmitter has the option to reduce the data transmission rate by applying a discount factor, denoted as θ, where $0 < \theta < 1$. With this discount rate, we can calculate the error probability for both single-hop and two-hop devices as:

$$\begin{aligned}
&P_{\mathrm{e}}^{1h} = \Pr\left(\exists i \in \mathcal{N}_{1h}, \theta \cdot \hat{r}_i^{d} > r_i^{d}\right), \\
&P_{\mathrm{e}}^{2h} = \Pr\left(\exists i \in \mathcal{N}_{2h}, \theta \cdot \hat{r}_{i,D_i}^{(1)} > r_{i,D_i}^{(1)} \cup \theta \cdot \hat{r}_i^{(2)} > r_i^{(2)}\right)
\end{aligned} \tag{13}$$

IV. PROPOSED METHOD FOR RELAY SELECTION AND TRANSMIT POWER OPTIMIZATION

In industrial subnetworks, minimizing the overall emitted power extends sensor battery time, and reduces interference in neighbor subnetworks. In this section, we propose a method for minimization of the total transmit power of all devices and APs, while coping with the timing constraints presented above. The optimization problem can be posed as

$$\min_{\mathbf{P}, \mathcal{N}_{1h}, \mathcal{N}_{2h}, \mathcal{D}} \left(\sum_{n \in \mathcal{N}} P_n + \sum_{n \in \mathcal{N}_{2h}} P_{D_n}^{s} \right), \tag{14a}$$

$$\text{s.t. } T^{DF} \le T_U, \tag{14b}$$

$$P_n \le P_{max}, \ \forall n \in \mathcal{N} \tag{14c}$$

$$P_{D_n}^{s} \le P_{max}, \ \forall n \in \mathcal{N}_{2h} \tag{14d}$$

where $\mathbf{P} = [P_1, P_2, \ldots, P_N, P_{D_1}^{s}, P_{D_2}^{s}, \ldots, P_{D_{N_{2h}}}^{s}]$ represents the vector of transmit powers for all devices, with $P_{\max}$ denoting the maximum permissible transmission power. Constraint (14b) addresses the requirement for low latency, while (14c) and (14d) set the power limits. Given the complexity of jointly selecting relays and minimizing power, our approach first identifies the optimal transmission link before minimizing transmit power. By assuming constant power, we reformulate the objective to identify the link that maximizes transmission rate, thereby reducing total delay. Following Laneman et al. [10], the average rate in DF relaying is given by $1/2 \cdot \min\left\{ r_{n,D_n}^{(1)}, r_n^{(2)} \right\}$. Assuming constant and equal power for P_n and $P_{D_n}^{s}$, we compute the minimum channel gain over both transmission phases for all potential relays, selecting the link with the highest gain, i.e., $\forall n \in \mathcal{N}, \forall k \in \mathcal{K}$ we have:

$$\mathbf{G}^{2h}(n,k) \triangleq \frac{1}{2} \min\left\{ |\mathbf{h}_c(k)|^2, |\mathbf{H}_s(n,k)|^2 \right\}, \tag{15}$$

$$\mathbf{g}^{2h}(n) \triangleq \max_k [\mathbf{G}^{2h}(n,1), \mathbf{G}^{2h}(n,2), \cdots, \mathbf{G}^{2h}(n,K)] \tag{16}$$

This metric is subsequently compared with the direct channel gain $|\mathbf{h}_p(n)|^2$ to ascertain whether direct or cooperative transmission is more advantageous. Should two-hop transmission prove preferable, the sAP exhibiting the maximum channel gain will be chosen for cooperative transmission. The comprehensive procedure is delineated in Algorithm 1.

Algorithm 1 Algorithm for classification of devices and relay selection

```
Input: The channel gains $\mathbf{h}_c(k)$, $\mathbf{H}_s(n,k)$, and $\mathbf{h}_p(n)$ for
  all $N$ devices and $K$ sAPs.
for $n = 1 : N$ do
    calculate $\mathbf{g}^{2h}(n)$ from (16)
    if $|\mathbf{h}_p(n)|^2 \ge \mathbf{g}^{2h}(n)$ then
        $n \to \mathcal{N}_{1h}$
    else
        $n \to \mathcal{N}_{2h}$
        select relay: $\arg\max_k \{\mathbf{G}^{2h}(n,:)\} \to D_n$
    end if
end for
Output: $\mathcal{N}_{1h}$, $\mathcal{N}_{2h}$, $\mathcal{D}$.
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Given the sets $\mathcal{N}_{1h}$, $\mathcal{N}_{2h}$, and $\mathcal{D}$, we proceed to minimize power consumption. This is achieved by simplifying the optimization problem outlined in (14) as follows:

$$\min_{\mathbf{P}} \left(\sum_{n \in \mathcal{N}} P_n + \sum_{n \in \mathcal{N}_{2h}} P_{D_n}^{s} \right), \tag{17a}$$

$$\begin{aligned}
\text{s.t. } & \sum_{n \in \mathcal{N}_{1h}} \frac{B_n}{W\theta \log_2\left(1 + \hat{g}_n^{d}\right)} \\
& + \sum_{n \in \mathcal{N}_{2h}} \frac{B_n}{W\theta \log_2\left(1 + \hat{g}_{n,D_n}\right)} \\
& + \sum_{n \in \mathcal{N}_{2h}} \frac{B_n}{W\theta \log_2\left(1 + \hat{g}_{D_n,p} + \hat{g}_n^{d}\right)} \le T_U,
\end{aligned} \tag{17b}$$

$$(14c) - (14d) \tag{17c}$$

where (17b) refers to the total time constraint. It is important to note that problem (17) is formulated for the general I-CSI case. For the P-CSI case, $\theta = 1$ and $T_U = T$. Problem (17) is hard to solve because of the non-convex constraint (17b), and thus finding the global optimum is generally intractable. To circumvent the non-convexity, we resort to SPCA where the problem is iteratively approximated by a sequence of convex programs. At each iteration, the non-convex constraint is replaced by convex surrogate that serves as approximation. Thus, let us rewrite the (17) as:

$$\min \left(\sum_{n \in \mathcal{N}} P_n + \sum_{n \in \mathcal{N}_{2h}} P_{D_n}^{s} \right), \tag{18a}$$

$$\text{s.t. } \sum_{n \in \mathcal{N}_{1h}} \frac{B_n}{\gamma_n^{d}} + \sum_{n \in \mathcal{N}_{2h}} B_n \left(\frac{1}{\gamma_{n,D_n}^{(1)}} + \frac{1}{\gamma_n^{(2)}} \right) \le T_U W \theta, \tag{18b}$$

$$\log_2\left(1 + \hat{g}_n^{d}\right) \ge \gamma_n^{d}, \quad \forall n \in \mathcal{N}_{1h}, \tag{18c}$$

$$\log_2\left(1 + \hat{g}_{n,D_n}\right) \ge \gamma_{n,D_n}^{(1)}, \ \forall n \in \mathcal{N}_{2h}, \tag{18d}$$

$$\log_2\left(1 + \hat{g}_{D_n,p} + \hat{g}_n^{d}\right) \ge \gamma_n^{(2)}, \ \forall n \in \mathcal{N}_{2h}, \tag{18e}$$

$$(14c) - (14d) \tag{18f}$$

where γ_n^{d}, $\gamma_{n,D_n}^{(1)}$, and $\gamma_n^{(2)}$ are auxiliary variables to approximate the non-convex terms with convex counterparts. It can be perceived that γ_n^{d}, $\gamma_{n,D_n}^{(1)}$, and $\gamma_n^{(2)}$ play the roles of lower bound for $\log_2\left(1 + \hat{g}_n^{d}\right)$, $\log_2\left(1 + \hat{g}_{n,D_n}\right)$, and $\log_2\left(1 + \hat{g}_{D_n,p} + \hat{g}_n^{d}\right)$, respectively. Increasing the lower-bound values and simultaneously reducing the upper-bounds will boost the left-side of the constraints, which is needed here, so that the constraints (18b)-(18e) would be active at the optimum. The (18b) is convex, since it is a linear combination of three quadratic terms over linear functions that is convex [11]. Affine approximations of constraints (18c)-(18e), $\forall n \in \mathcal{N}$ are given by:

$$1 + \rho_n - 2^{\gamma_n^{d}} \ge 0, \ \forall n \in \mathcal{N}_{1h}, \tag{19a}$$

$$\rho_n \leq \frac{P_n|\mathbf{h}_p(n)|^2}{\sigma_0^2}, \ \forall n \in \mathcal{N}_{1h}, \tag{19b}$$

$$1 + \psi_n - 2^{\gamma^{(1)}_{n,D_n}} \geq 0, \ \forall n \in \mathcal{N}_{2h}, \tag{19c}$$

$$\psi_n \leq \frac{P_n|\mathbf{H}_s(n, D_n)|^2}{\sigma_0^2}, \ \forall n \in \mathcal{N}_{2h} \tag{19d}$$

$$1 + \zeta_n - 2^{\gamma^{(2)}_n} \geq 0, \ \forall n \in \mathcal{N}_{2h}, \tag{19e}$$

$$\zeta_n \leq \frac{P^s_{D_n}|\mathbf{h}_c(D_n)|^2 + P_n|\mathbf{h}_p(n)|^2}{\sigma_0^2}, \forall n \in \mathcal{N}_{2h}, \tag{19f}$$

where ρ_n, ψ_n, and ζ_n, are auxiliary variables.

Thus, by replacing constraints (18c)–(18e) with (19), the optimization problem (18) transforms into a standard convex semidefinite programming (SDP). This can be efficiently solved using numerical solvers, such as the SDP tool in CVX [11].

V. SIMULATION RESULTS

In this section, our proposed solution is evaluated via Monte Carlo simulations. We consider a 3×3 m^2 subnetwork, serving 20 sensors. This can be the case of a production module in a factory. Sensors and APs are uniformly distributed in the subnetwork area. The pAP is expected to receive a 32 bytes packet from each sensor in a total time of $0.1\mathrm{ms}$ and bandwidth of $100\mathrm{MHz}$. Moreover, the power spectral density of the additive white Gaussian noise is -174 dBm/Hz. The wireless channels between the device and APs, as well as between the sAP and pAP, are assumed to undergo independent frequency-flat Rayleigh fading. The path loss model is determined using the factory and open-plan building channel model from [5]. In accordance with [12], we assume a shadow fading model in our scenario with a standard deviation of 7 dB.

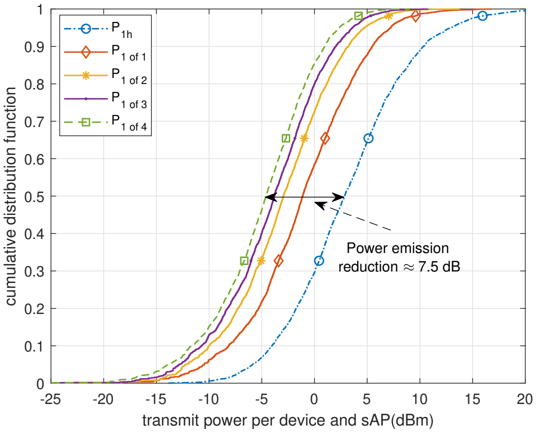

Fig. 3: Comparing CDF of transmit power across various schemes with for $P_{max} = 20$ dBm

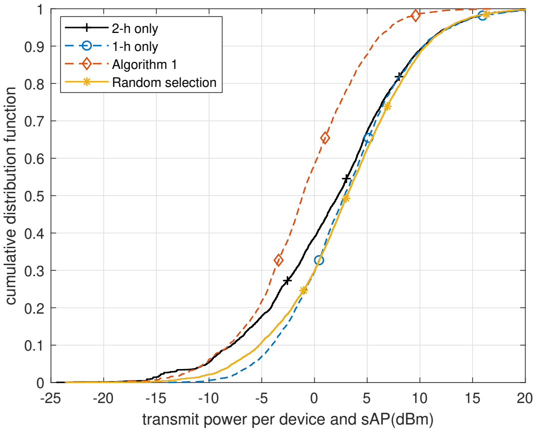

Fig. 4: Comparing transmit power CDFs for various device classification methods

We consider cooperative schemes with different number of sAPs to be possibly selected, including '1h' and '1 of K'. In Fig.3, we compare the empirical cumulative distribution function (CDF) of the transmission power per devices and sAPs for various schemes, assuming $P_{max} = 20$ dBm. Results show a reduction of the transmit power ranging from 4 dB to 7.5 dB for the two-hop schemes with respect to the single-hop scheme. This reduction can be attributed to the possibility of selecting relays in advantageous propagation conditions with respect to the link with the pAP. Clearly, by increasing the number of sAPs, greater power savings can be achieved. However, it is evident that the difference in this power gain diminishes as the value of K becomes large. To evaluate the performance of Algorithm 1, we compare the transmit power CDFs in Fig. 4 under the following scenarios: 1) All devices employ cooperative transmission, 2) All devices transmit directly to the pAP, 3) Devices are classified for single-hop or two-hop operations according to the classification method in Algorithm 1, and 4) Random selection of devices, categorized as single-hop or two-hop devices. In this simulation, we set $P_{\max} = 20$ dBm, and only one sAP is available (i.e., '1 of 1'). It is evident that all the classification methods require higher power compared to Algorithm 1, confirming the efficacy of this method in power reduction. Fig. 5 depicts the time overflow rate across different power levels for various schemes. These findings are derived using maximum power and are independent of the actual power optimization process. As the power optimization method adjusts power to meet time constraints, it defaults to the maximum power in worst-case scenarios. However, if this power level remains insufficient, overflow occurs. In the I-CSI case, we set $L = 4$, allocating less than 1% of time resources to the training stage. To minimize channel estimation error, maximum power is applied during the training stage, followed by the use of the power control method for the remaining time slot. The influence of training phase on average power transmission can be considered negligible. The results are presented for $\theta = 0.5$ and $\theta = 0.9$ in the I-CSI case, compared with the ideal P-CSI case. The trend indicates that as θ increases, the overflow rate decreases and approaches the case of P-CSI. For $P_{\max} = 30$ dBm, all two-hop transmissions satisfy the minimum overflow rate requirement of 10^{-6} even in the I-CSI case with $\theta = 0.5$, while the single-hop transmission cannot achieve better than 2×10^{-4}. Particularly in the P-CSI scenario, the '1 of 4' scheme achieves an overflow rate of 10^{-6} for $P_{\max} = 5$ dBm, whereas the single-hop approach registers a rate no better than 0.1, indicating a significant gap.

In Fig. 6, we show the impact of the discount factor on

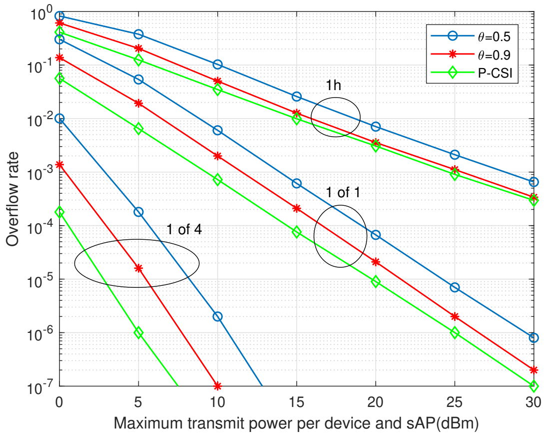

Fig. 5: Overflow rate against maximum transmit power of different schemes for P-CSI case and I-CSI case with $L = 4$.

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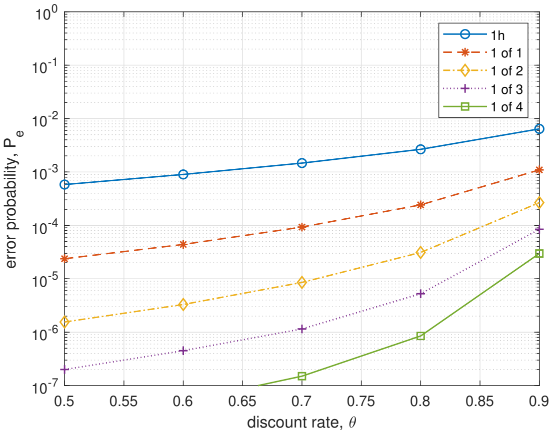

Fig. 6: P_e against θ for I-CSI case with $P_{max} = 25$ dBm and $L = 4$.

the error probability, comparing results for $\theta = 0.5 \sim 0.9$. It is important to remark that the overflow rate and error probability represent conflicting requirements: as the discount factor approaches 1, the overflow rate decreases since sensor packets might be mapped onto a smaller amount of resources. However, this leads to a higher error probability. Conversely, reducing the value of θ leads to a higher power demand to meet stringent low-latency requirements. To maintain an acceptable overflow rate according to the results in Fig. 5, $P_{\max}$ is set here to 25 dBm. The '1 of 3' and '1 of 4' schemes successfully meet the specified constraint of $P_e < 10^{-6}$ for θ values below 0.7 and 0.8, respectively. Conversely, other schemes fail to meet this constraint. It is worth to mention that, a discount factor in the order of 0.7∼0.8 only leads to around 1 dB power increase with respect to the P-CSI case. The possibility of using a limited discount factor (and subsequently a limited power increase) is due to the generally advantageous propagation conditions in a short-range subnetwork.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we have addressed the challenge of supporting communication with tight cycle time for many sensors within an industrial wireless subnetwork. Our solution relies on the presence of multiple secondary APs with relaying capabilities, and a novel communication protocol for accommodating devices operating in a single-hop or a two-hop fashion. We also addressed the problem of minimization of the emitted power while coping with the timing constraints. Simulation results validated the effectiveness of the proposed protocol. Specifically, using a '1 of 4' scheme results in a 7.5 dB power reduction compared to single-hop transmission with optimized transmit power. Additionally, employing a transmit power of 25 dBm in the P-CSI scenario, the overflow rate decreases from 9×10^{-4} during single-hop transmission to 10^{-6} using the '1 of 1' scheme. Meanwhile, the '1 of 4' configuration attains a 10^{-6} rate with just 5 dBm.

Future work will extend the analysis to amplify and forward relaying in subnetworks, and address the support of services with heterogeneous requirements in the cooperative framework, leveraging flexible/full duplexing capable APs.

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