This document is a preprint of: A.H. Mahdi, T. Hossler, N. Franchi et al., "Multi-Connectivity for Reliable Wireless Industrial Communications: Gains and Limitations," in Proceedings of 2020 IEEE Wireless Communications and Networking Conference (IEEE WCNC 2020), Seoul, South Korea, Apr 2020.

Multi-Connectivity for Reliable Wireless Industrial Communications: Gains and Limitations

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***Abstract*—Realizing wireless mission-critical applications in industry, such as closed-loop control, necessitates ultra-reliable low-latency communications (URLLC) to achieve error-free message transmission with hard real-time requirements. Recently, multi-connectivity (MC) has been introduced as a promising scheme to ensure URLLC in Industry 4.0. However, implementing MC in mobile industrial communications rises multiple technical challenges, such as avoiding degradation in reliability due to fading and the shadowing effect, and managing multiple links in parallel which increases signaling overhead dramatically. To deal with these challenges, this paper investigates the gains and limitations of implementing MC in industrial wireless communications. It studies conflicting optimization problems using MC based on different radio parameters. Also, a link management scheme is introduced for MC to reduce the signaling overhead based on different radio parameters. The simulation results demonstrate gains and limitations of using MC and the selected parameters (frequency reuse factor, number of users, and frequency band) on the reliability and the signaling overhead in industrial communications.**

***Index Terms*—Multi-connectivity, URLLC, network deployment, maximum ratio combining, link management, signaling overhead.**

I. INTRODUCTION

Wireless applications have been applied in different fields, such as industry to perform remote access tasks, efficient monitoring, on site services, etc. with flexibility during mobility. However, some wireless industrial applications require high reliability and deterministic low latency (such as mission critical applications, closed-loop control, etc.) to meet the desired requirements (safety, accuracy, etc.) [1]. Achieving such requirements using wireless communications may suffer from different issues such as link degradation, fading channel, shadowing, and interference which increase the outage probability of communication [2]. One of the proposed solutions to overcome the aforementioned issues and to improve the reliability is multi-connectivity (MC). The basic idea of MC is to transmit same packets over multiple links (in spatial and/or frequency domain) to the mobile user (MU) by coordinating access points (APs) in proximity. MU combines different copies of packet using combining schemes, such as maximum ratio combining (MRC), which improves the reliability by orders of magnitude [3].

The achievable reliability over MC mainly depends on the degree of overlap between the coverage of APs in proximity, the frequency reuse factor, pathloss, line-of-sight (LoS) path blockage and interference from neighbouring APs. Deploying a network with MC capabilities is related to inter-access point distance (IAD) and the available frequency resources at each AP. In addition to the network deployment, applying MC to MUs necessitates instantaneous link management to perform handover efficiently and against different issues such as frequent simultaneous handover of links, inefficient resource consumption, etc. which negatively influence the communication's reliability and increase the signalling overhead on the network.

Several works have investigated the aforementioned issues in network deployment despite most of them have focused on road-side units and remote radio heads for vehicular communication. In [4], the authors proposed APs deployment based on transmission range using a cumulative weight based method to reduce the number of deployed APs. The authors in [5] aimed to maximize the centrality of a 2D grid deployment of AP using the Knapsack problem. In [6], the authors reduced the number of the deployed APs using heuristic algorithms under time of delivery as a constraint. Authors in [7], [8] proposed dual-connectivity based heterogeneous networks using macro-/micro-cells. However, link-failure due to fading and shadowing was not considered.

In addition to the deployment issue, different previous works have recognized the link management issue. In [9], a link selection scheme has been proposed using MC to multiple APs in proximity. The proposed scheme adds (or drops) links in greedy behavior based on the signal strength, regardless the network capacity and number of users. In addition, the authors in [10] proposed the seamless dual-link HO for high-speed rail with a detailed study on signaling overhead. In [11], the issues of dual-connectivity, using carrier aggregation, in LTE systems were investigated, such as scheduling and cell association between the macro-cell and micro-cell.

Although different deployment and handover schemes have been studied, considering MC with link shadowing under high reliability constraints and low signalling overhead, many challenges have not been investigated. In this paper, communication reliability and signaling overhead are expressed in terms of communication outage and link management probabilities. MC with different numbers of links and users using different frequency reuse factors, as well as different frequency bands in industrial communications are considered. The contributions of this work are as follows:

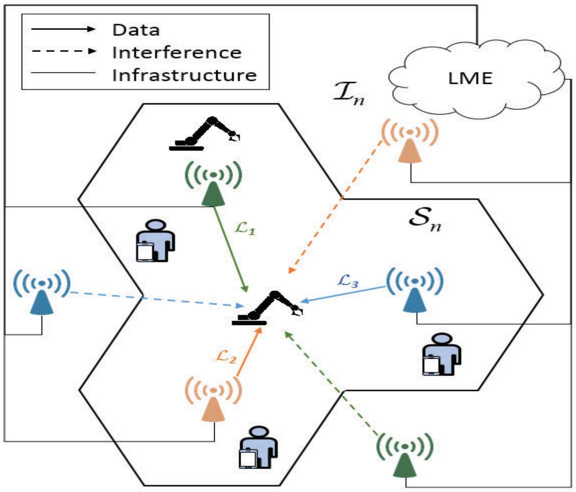

Figure 1. System Model of an industrial hall with deployed APs to serve MUs using MC with $K = 3$ links and frequency reuse factor $\kappa = 3$. The Link Management Entity (LME) is responsible for monitoring and link management

- Deriving an expression for outage probability in MC considering shadowing.
- Introducing a new scheme for link management using MC in a mobility scenario.
- Deriving an expression for link management probability using MC, which reflects the probability of signaling overhead.
- Investigating the influence of IAD, frequency reuse factor, number of connected links, number of users, and frequency bands on outage probability as well as the link management probability.

The remainder of the paper is organized as follows: Section II describes the system model. The problem formulation is presented in Section III. The proposed solutions for network deployment and link management are explained in Section IV. Section V presents the simulation scenario and discusses the results. Finally, section VI summarizes this work.

II. SYSTEM MODEL

In this work, a system model of an industrial hall of length L, width W, and height H is considered as depicted in Fig. 1. The model includes set of distributed APs in the industry hall, which are denoted by $\mathcal{A}_v, v \in \{1, 2, \ldots, V\}$. They are separated by the IAD r_{IAD}. In addition, the model includes a set of MU, which are denoted by $\mathcal{U}_n$, $n \in \{1, 2, \ldots, N\}$, distributed in the industry hall. For a user $\mathcal{U}_n$ at position x_n, y_n, z_n, $(x_n < W, y_n < L, z_n < H)$, the distance from $\mathcal{A}_v$, at position $(\mathcal{A}_v^x, \mathcal{A}_v^y, \mathcal{A}_v^z)$, is given by

$$r_{\mathcal{A}_v\mathcal{U}_n} = \sqrt{(x_n - \mathcal{A}_v^x)^2 + (y_n - \mathcal{A}_v^y)^2 + (z_n - \mathcal{A}_v^z)^2}. \quad (1)$$

The pathloss between $\mathcal{A}_v$ and $\mathcal{U}_n$ is modelled as

$$\Theta_{\mathcal{A}_k\mathcal{U}_n} = \Theta_0 \left(\frac{r_{\mathcal{A}_v\mathcal{U}_n}}{r_0}\right)^{\alpha}, \quad (2)$$

$$\Theta_0 = \left(\frac{4\pi r_0 f_c}{C}\right)^2,$$

where r_0 is reference distance (1 m), f_c is the carrier frequency (in Hz), C is speed of light (3×10^8 m/s), and α is the pathloss exponent.

MC is considered in the downlink where more than one AP transmits a packet to $\mathcal{U}_n$ which combines the packets using MRC. Thus, each $\mathcal{U}_n$ is equipped with M radio receiver branches to combine the received packets from the connected APs, hence, $\mathcal{U}_n$ has a set of simultaneous links $\mathcal{L}^n = \{\mathcal{L}_1^n, \mathcal{L}_2^n, \ldots, \mathcal{L}_K^n\}$ with cardinality $|\mathcal{L}^n| = K \leq M$. Thus, K APs are connected to $\mathcal{U}_n$. For a system with the number of links K and frequency reuse factor κ, the set of APs connected to $\mathcal{U}_n$ is denoted as $\mathcal{S}_n$. For every connected AP, there is a set of interfering APs that reuse same frequency channel based on κ and the IAD r_{IAD}, which is denoted as $\mathcal{I}_n$.

For readability, the superscript is discarded in the following text when values of k and κ are fixed. At any position of $\mathcal{U}_n$ in the industry hall, the received signal-to-noise-plus-interference ratio (SINR) at the kth link is given as

$$\Gamma_{n,k} = \frac{P_{\mathcal{A}}\mathcal{W}_{\mathcal{U}}G_{\mathcal{A}}G_{\mathcal{U}}\ \Theta_{\mathcal{A}_k\mathcal{U}_n}}{\mathcal{N}_0\mathcal{W}_{\mathcal{U}} + \sum_{j\in\mathcal{I}_n} P_{\mathcal{A}}\mathcal{W}_{\mathcal{U}}G_{\mathcal{A}}G_{\mathcal{U}}\ \Theta_{\mathcal{A}_j\mathcal{U}}}, \quad (3)$$

where $P_{\mathcal{A}}$ is the power spectral density of $\mathcal{A}_k$, $\mathcal{W}_{\mathcal{U}}$ is the downlink bandwidth for one user, $G_{\mathcal{A}}$ and $G_{\mathcal{U}}$ are antenna gains of AP and MU, respectively, and $\mathcal{N}_0$ is the power spectral density of the additive white Gaussian noise (AWGN). In addition to aforementioned parameters, shadowing is considered in the industry hall and has impact on the links to the connected APs, as well as interfering APs. The shadowing is modeled in lognorm distribution with predefined standard deviation Σ_S. The total received SINR of $\mathcal{U}_n$ after using MRC is

$$\Gamma_n^{\text{MRC}} = \sum_{k\in\mathcal{S}_n} \Gamma_{n,k}. \quad (4)$$

$\mathcal{U}_n$ is said to be in outage whenever the instantaneous downlink transmission rate falls below the required transmission rate. Let $\mathcal{P}_b$ denote the frame size in bits and T be the frame duration. Then, $\mathcal{U}$ is in outage if $\mathcal{W}_{\mathcal{U}} \log_2\left(1 + \Gamma_n^{\text{MRC}}\right) < \frac{\mathcal{P}_b}{T}$.

During mobility of $\mathcal{U}_n$ variations on Γ_k occur and different handover events could be triggered (e.g. serving AP becomes worse than threshold (A2), neighbor AP becomes offset better than serving AP (A3), neighbor AP becomes better than threshold (A4)) for each link [12]. To perform such functionalities efficiently under the constraint of seamless handover, a link management entity (LME) is introduced. It monitors Γ_k to trigger the appropriate action (add/drop link, handover link). In addition, the LME is responsible for selecting the proper modulation and coding scheme based on Γ_{MRC} to ensure high data rate under the constraint of reliable communication.

III. PROBLEM FORMULATION

A. Deployment Consideration

Network deployment plays a significant role in reliable communication using MC, due to ensuring coverage to MU from APs in proximity. To satisfy a required outage probability constraint, three different factors in network deployment should be considered: frequency reuse κ, degree of MC K and number of users N_v served by AP $\mathcal{A}_v$. In the following, these factors are described in detail.

1) Frequency reuse: Let the total available bandwidth be denoted by $\mathcal{W}_{\text{tot}}$. This bandwidth must be utilized across all APs. Then, for a given frequency reuse factor κ, bandwidth available at one AP is $\mathcal{W}_{\mathcal{A}} = \mathcal{W}_{\text{tot}}/\kappa$. Increasing κ decreases interference between neighbouring APs, but bandwidth available at an AP is also decreased. By considering a single user served by an AP, the instantaneous downlink transmission rate on a single $\mathcal{A} - \mathcal{U}$ link is given by

$$\mathcal{C}\left(\kappa,\, K = 1,\, N = 1\right) = \frac{\mathcal{W}_{\text{tot}}}{\kappa}\, \log_2\left(1 + \Gamma_{n,k}\right). \tag{5}$$

2) Multi-user provisioning in MC: By assuming an equal number of users per AP, denoted by N_v, across all APs in the industry hall and a single link per user ($K = 1$), an AP serves N_v users simultaneously using frequency-division-multiple-access (FDMA). However, using K links, K APs transmit multiple copies of data packet to MU; hence, the available bandwidth for each downlink MU results in

$$\mathcal{W}_{\mathcal{U}} = \frac{\mathcal{W}_{\mathcal{A}}}{N\, K}. \tag{6}$$

Using (5), the downlink transmission rate for a $\mathcal{A}_v$-$\mathcal{U}_n$ link is

$$\mathcal{C}\left(\kappa,\, K,\, N\right) = \frac{\mathcal{W}_{\text{tot}}}{N\,\kappa\, K}\, \log_2\left(1 + \Gamma_n^{\text{MRC}}\right). \tag{7}$$

The outage in communication occurs when $\mathcal{C}\left(\kappa, K, N\right) < \frac{\mathcal{P}_b}{T}$. Then, the outage probability is $\Pr\left(\Gamma_n^{\text{MRC}} < \Gamma_{\text{th}}\right)$, where Γ_{th} is

$$\Gamma_{\text{th}} = 2^{\frac{\mathcal{P}_b\, N \kappa\, K}{T \mathcal{W}_{\text{tot}}}} - 1. \tag{8}$$

B. Multi-Connectivity Management

MC has been presented in literature as a promising scheme to achieve URLLC [3]. However, optimizing the number of links using MC and its influence on signalling overhead has not yet been investigated. In the aforementioned system model, the LME optimizes the total number of links allocated to users according to

$$\min \sum_{n=1}^{N} |\mathcal{L}^n|, \tag{9a}$$

$$\text{s. t.} \quad |\mathcal{L}^n| \leq M \quad \forall n \in \{1, 2, \ldots, N\}, \tag{9b}$$

$$\Gamma_n^{\text{MRC}} \geq \Gamma_{\text{th}} \quad \forall n \in \{1, 2, \ldots, N\}. \tag{9c}$$

Solving such a problem requires a centralized control unit which optimizes the total number of links of all users frequently due to their mobility. In recent technologies, optimizing the number of link in MC is based on heuristic schemes of conventional handover per $\mathcal{U}_n$, which follows handover events defined in 3GPP [9], [12]:

$$\text{A2}: \quad \Gamma_{n,k} \leq \max_{k \in K} \Gamma_{n,k} - \Gamma_{\text{D}}, \quad \text{(Drop link)} \tag{10a}$$

$$\text{A3}: \quad \Gamma_{n,k} + \mathcal{H}_s \leq \Gamma_p \quad \text{(Handover link)} \tag{10b}$$

$$\text{A4}: \quad \Gamma_p \geq \max_{k \in K} \Gamma_{n,k} - \Gamma_{\text{A}}, \quad \text{(Add link)}, \tag{10c}$$

where Γ_{A} and Γ_{D} are offset windows for adding and dropping links, $\mathcal{H}_s$ is the hysteresis, and $\Gamma_{n,p}$ is the SINR of the pth link to the non-serving $\mathcal{A}_p$ in proximity. To avoid ping pong effects, there should be an offset q between Γ_A and Γ_D (i.e., $\Gamma_D = \Gamma_A + q$), hence, dropping the kth link could occur only if its $\Gamma_{n,k}$ degraded deeply [9].

However, the aforementioned conditions push the system toward increasing $|\mathcal{L}^n|$ to maximize Γ_n^{MRC} due to adding (and keeping) every link in proximity while it has high SINR,

$$\max \sum_{k=1}^{M} \Gamma_{n,k} \tag{11a}$$

$$\text{s. t.} \quad \Gamma_p \geq \max_{k \in K} \Gamma_{n,k} - \Gamma_{\text{A}} \tag{11b}$$

$$\Gamma_{n,k} \geq \max_{k \in K} \Gamma_{n,k} - \Gamma_{\text{D}}. \tag{11c}$$

Increasing the number of links per user reduces its assigned bandwidth $\mathcal{W}_{\mathcal{U}}$. Thus, the optimization problem in (11) conflicts with optimization problem in (9) and the the whole system ends with highest number of links. In addition, increasing number of links increases signalling overhead in the network because the frequent request of link addition, dropping and handover due to mobility of user which increases the traffic on control channel. Thus, high background latency will be generated. In the next section, a solution is proposed to cope with this conflict.

IV. PROPOSED SOLUTIONS

A. Multi-link based Network Deployment

1) Calculation of outage probability: For simplicity, it is considered that random shadowing only on the nearest two links, and the effect of shadowing on links from other APs is negligible. Thus, the following analysis gives the upper bound on the outage performance. Considering log-normal shadowing with standard deviation σ_S, the outage probability for fixed position $(x,\, y)$ is as given in (21) in Appendix A. Further solving, the outage probability is calculated as given in (22). The overall outage probability for a given r_{IAD}, κ and K is obtained by averaging over the uniform random variables $x,\, y$ and is given by (12). The integral in (12) can be solved numerically.

2) Optimizing inter-access point distance: The objective is to optimize the IAD r_{IAD}, such that the desired outage performance is achieved for given values of frequency resuse factor κ, MC factor K and number of users per cell N_v. The optimization problem of network deployment is written as

$$\max \quad r_{\text{IAD}} \tag{14}$$

$$\text{s. t.} \quad P_{\text{out}} < \epsilon, \tag{15}$$

where ϵ is the tolerable outage probability. This optimization problem can be solved numerically.

B. Link Management

Optimizing the number of assigned links per user improves the system capacity and ensures the stability of reliability, as well as reducing signaling overhead on the network side.

In this paper, a new scheme for link management in MC is proposed based on Γ_{MRC} as a metric (for communication

$$P_{\text{out}} = \int\limits_{0}^{L} \frac{1}{L} \int\limits_{0}^{W} \frac{1}{W} \int\limits_{-\infty}^{\log\left(\frac{\overline{\Gamma_{\text{th}}}(x,\, y)}{\Gamma_{k+1}(x,\, y)}\right)} \left(1 - \mathcal{Q}\left(\frac{1}{\sigma_S}\, \log\left(\frac{\overline{\Gamma_{\text{th}}}\,(x,\, y) - \Gamma_{k+1}\,(x)\, e^{w}}{\Gamma_k\,(x,\, y)}\right)\right)\right) \frac{1}{\sqrt{2\pi}\sigma_S} \exp\left(\frac{-w^2}{2\sigma_S^2}\right) \partial w\, \partial x\, \partial y. \tag{12}$$

$$P_{\text{LM}} = \int\limits_{0}^{L} \frac{1}{L} \int\limits_{0}^{W} \frac{1}{W} \left(1 - \left(\left(1 - P_{\text{LH}}(x,\, y)\right)\left(1 - P_{\text{LD}}(x,\, y)\right)\left(1 - P_{\text{LA}}(x,\, y)\right)\right)\right) \partial x \partial y. \tag{13}$$

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performance) to manage $\mathcal{L}_n$ based on a minimum Γ_{L} as a reliability requirement as follows:

$$\min_{K \in M} K \tag{16a}$$

$$\text{s. t.} \quad \Gamma_n^{\text{MRC}} \geq \Gamma_{\text{th}} \tag{16b}$$

The proposed scheme is based on three different actions:

- **Add Link** from the non-connected neighbor $\mathcal{A}_v$, which is triggered only under condition ($\Gamma_{\text{MRC}}^{n} \leq \Gamma_{\text{th}}^{n}$). The probability of adding a link is denoted by

$$P_{\text{LA}} = \Pr\left(\Gamma_n^{\text{MRC}} \leq \Gamma_{\text{th}}\right). \tag{17}$$

- **Drop Link** from the connected APs,which is triggered only if $\Gamma_{\text{MRC}}^{n} \geq \Gamma_{\text{th}}$. The probability of a link drop is denoted by

$$P_{\text{LD}} = \Pr\left(\Gamma_n^{\text{MRC}} \geq \Gamma_{\text{th}}\right). \tag{18}$$

- **Handover Link** triggers link handover between serving AP $\mathcal{L}_{n,k}$ and neighbor AP $\mathcal{L}_p$ based on the A3 event in (10) without modifying $|\mathcal{L}^n|$. The probability of a link switch is denoted by

$$P_{\text{LH}} = \Pr\left(\Gamma_{n,k} + \mathcal{H}_s \leq \Gamma_p\right). \tag{19}$$

The probability of link management in the industry hall is related to probability of three aforementioned actions and is given by (13). More details regarding deriving this formula are found in Appendix B.

V. SIMULATION RESULTS

To study the gains and limitations of MC in terms of deployment and link management, an exemplary scenario of an industrial hall with hexagonal deployment is evaluated.

The outage and link management probabilities against different network deployments are investigated using numerical simulations. The considered industrial scenario is depicted in Fig. 1 and contains MC communications using downlink (DL) for MUs (robots and HMI). The desired QoS comprises a video streaming of mission critical applications, which requires high data rate R_b (14 Mbps) and low outage threshold ϵ (10^{-6}). The values of other simulation parameters are given in Table I. N is the number of MUs per cell which are served by neighbor access points and share the full bandwidth of APs in $\mathcal{S}_n$, as shown in Fig. 2.

In the following numerical simulation the impact of different control parameters on reliability and signalling overhead have been studied, such as IAD r_{IAD}, frequency reuse factor κ, and number of links K. In addition to the aforementioned parameters, impact of different frequency band $\mathcal{B}$ is already studied. Each $\mathcal{B}$ has different parameters such as free-space pathloss Θ_0, pathloss exponent α, shadowing σ_S, as well as bandwidth $\mathcal{W}_{\text{tot}}$. These different parameters across different $\mathcal{B}$ have trade-off between high $\mathcal{W}_{\text{tot}}$ and Γ^{MRC} (due to pathloss parameters such as Θ_0, α, and σ_S) which affect reliability as given in Table II [2].

Table I
SIMULATION PARAMETERS

	Parameter	Value
Setup	Transmit power $P_{\mathcal{A}}$ [dBm/20MHz]	23
	Antenna gain of AP $G_{\mathcal{A}}$ [dBi]	3
	Antenna height $\mathcal{A}_v^z$ [m]	6
	Industry hall's dimensions $L \times W$ [m]	120×120
MU	Receiver sensitivity P_{min} [dBm]	-87
	Antenna gain of MU $G_{\mathcal{U}}$ [dBi]	3
	Antenna height of MU z_n [m]	1.5
	Number of users N	$\{1, 10, 20\}$
Network	Deployment strategy	Hexagonal
	Frequency re-use factor κ	$\{1, 4, 7\}$
	Number of links K	$\{2, 3\}$
QoS	Data Rate R_b [Mbps]	100
	Outage threshold ϵ	10^{-6}
Channel	Noise power density $\mathcal{N}_0$ [dBm/MHz]	-104
	Noise figure [dB]	7

Table II
PARAMETERS OF DIFFERENT FREQUENCY BANDS $\mathcal{B}$

$\mathcal{B}$ [GHz]	$\mathcal{W}_{\text{tot}}$ [MHz]	Θ_0 [dB]	α	σ_S [dB]
2.4	60	40	3.44	8.63
3.7	100	43	3	7.2
5.2	160	46	2.59	6.09

A. Outage Probability

In this subsection, the gains and limitations of outage probability per user in multi-user scenario using MC are evaluated based on number of links K, IAD r_{IAD}, number of users N, frequency band $\mathcal{B}$, and the frequency reuse factor κ.

Figure 3 shows the achievable reliability in terms of P_{out} of a single MU against r_{IAD} using different numbers of links K and different bands $\mathcal{B}$ at $\kappa = 4$. Decreasing the number of APs (or increasing r_{IAD}) improves the reliability due to reducing

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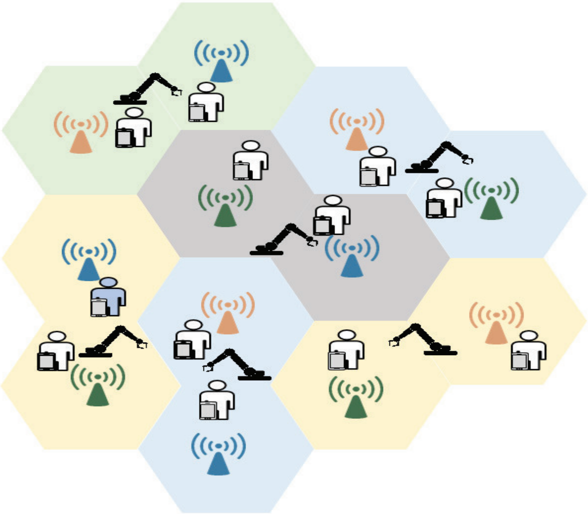

Figure 2. Multiple users served by cells in proximity (of same cell color $\mathcal{S}_n$) for $K = 2$, $\kappa = 2$, and $N = 3$. APs of different cells with similar color of serving APs are belong to $\mathcal{I}_n$.

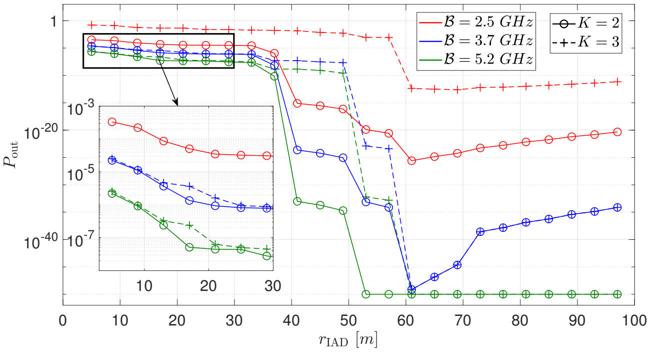

Figure 3. Outage probability P_{out} of a single MU against IAD r_{IAD} using different bands $\mathcal{B}$ and different links K and frequency reuse factor $\kappa = 4$.

co-channel interference from neighbor cells. Increasing the number of links K reduces the user’s bandwidth $W_{\mathcal{U}}$ and, hence, increases Γ_{th} which reduces the reliability, as in (7). To overcome such degradation, applying high $\mathcal{B}$ improves reliability under high K, although it has high pathloss Θ. This improvement is due to wide total bandwidth $\mathcal{W}_{\text{tot}}$ which ensures the required bandwidth $\mathcal{W}_{\mathcal{U}}$ for MU while increasing K, in spite of decreasing Γ^{MRC}, as in (5) due to high pathloss due to the frequency band and farthest connected APs. However, high K does not achieve a gain in reliability, compared to low K.

Figure 4 shows P_{out} against r_{IAD} using different numbers of links K and different bands $\mathcal{B}$ in a multi-user scenario ($N = 20$) and frequency reuse factor $\kappa = 4$. Increasing K improves the reliability (decreases P_{out}) using different bands due to increasing Γ^{MRC} based on (4). However, the gain in reliability due to high K is limited to r_{IAD} due to the increase in pathloss Θ from farthest APs which degrades Γ^{MRC} and becomes equivalent to low K. Although using high $\mathcal{B}$ with high K improves the reliability, the reliability keeps decreasing at high IAD ($r_{\text{IAD}} > 61$ m).

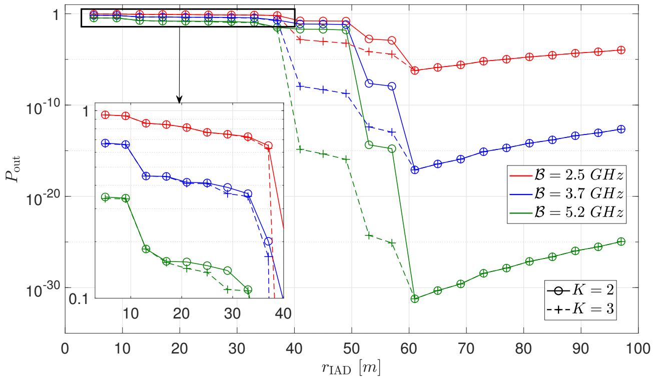

Figure 4. Outage probability P_{out} against IAD r_{IAD} for different bands $\mathcal{B}$, different links (K), and fixed frequency reuse (κ=4) in a multi-user scenario ($N = 20$).

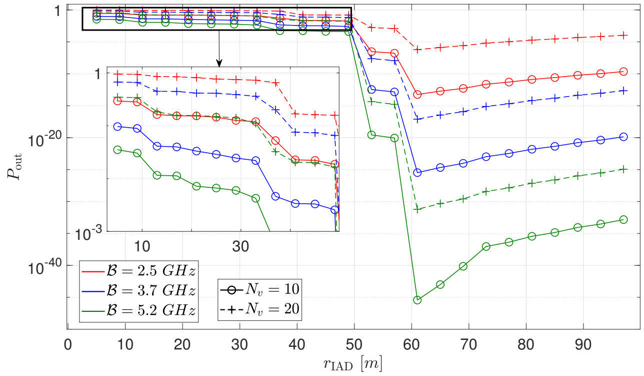

Figure 5. Outage probability P_{out} against IAD r_{IAD} for different bands $\mathcal{B}$ using dual-connectivity ($K = 2$) and fixed frequency reuse (κ=4) in multi-user scenario.

Figure 5 shows P_{out} against r_{IAD} for the multi-user scenario using different frequency bands $\mathcal{B}$, different number of users N, as well as dual-connectivity ($K = 2$) and frequency reuse factor $\kappa = 4$. In general, the behavior of P_{out} is similar to Fig. 4. However, high N reduces the user’s bandwidth $\mathcal{W}_{\mathcal{U}}$ which increases Γ_{th} and in turn degrades reliability (increases P_{out}). Thus, increasing K is limited to N in order to meet desired QoS requirements. Using a high frequency band $\mathcal{B}$ (high $\mathcal{W}_{\text{tot}}$) ensures higher $\mathcal{W}_{\mathcal{U}}$, which overcomes the impact of high pathloss on γ_k and Γ^{MRC} to meet the desired QoS requirements (Γ_{th} and ϵ).

B. Link Management

In this subsection, the impact of MC on signaling overhead, based on link management, is investigated under different control parameters. The probability of signaling overhead is reflected by the probability of link management P_{LM} in (13) and in Appendix B.

Figure 6 shows P_{LM} against different frequency bands $\mathcal{B}$ at $r_{\text{IAD}} = 61$ m (due to maximum achievable reliability

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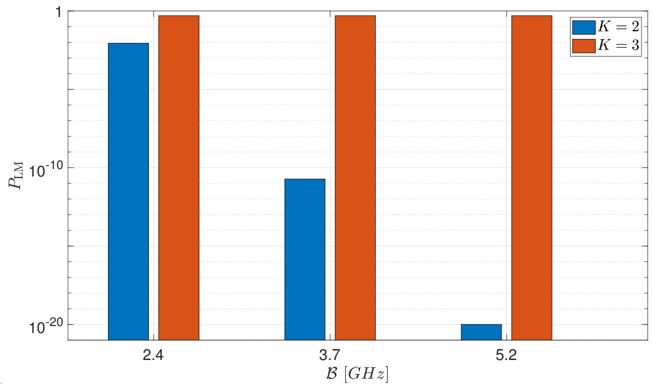

Figure 6. Probability of link management P_{LM} against different frequency band $\mathcal{B}$ at $r_{\mathrm{IAD}} = 61$ m using different number of links K, fixed frequency reuse factor (κ = 4), and fixed number of users (N= 20).

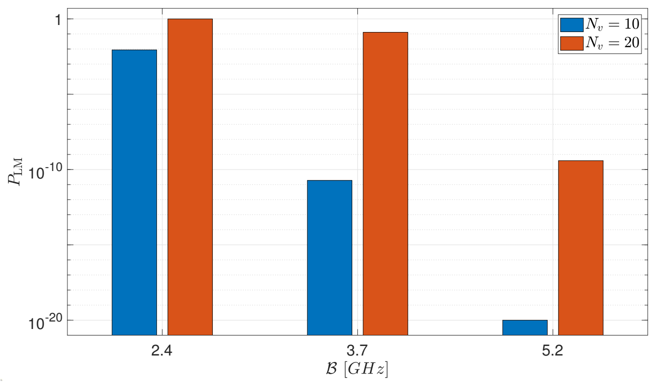

Figure 7. Probability of link management P_{LM} against different frequency band $\mathcal{B}$ at $r_{\mathrm{IAD}} = 61$ m using different numbers of users N, frequency reuse factor κ = 4, and dual-connectivity K= 2.

at this IAD) using different numbers of links K, frequency reuse factor κ = 4, and a fixed number of users N= 20. Increasing K increases the frequency of link management (P_{LA}, P_{LD}, and P_{LH}) as in (29), (27) and (30), respectively. Such a dramatically incremented P_{LM} occurs regardless of the frequency band $\mathcal{B}$. Thus, a high degree of MC has a negative impact on the signalling overhead on the network side.

Figure 7 shows the probability of link management P_{LM} against different frequency bands $\mathcal{B}$ using different numbers of users N, frequency reuse factor $\kappa = 4$, and dual-connectivity K= 2. Increasing N increases Γ_{th} as in (8) which increases P_{LA} as in (29). Thus, the signalling overhead is increased.

VI. CONCLUSION

In this paper the performance of MC in wireless industrial communications has been investigated, which optimizes the reliability and signaling overhead using different radio parameters. Increasing number of links in wireless industrial communications shows gain in reliability of DL communications. However, MC has limitations due to restricted values of IAD, number of users per cell, and frequency band which decrease the reliability. These conditions have been investigated in this paper. In addition to reliability, signalling overhead is another metric which has been investigated. Applying high number of links has limitation in term of signalling overhead due to frequent link management processes. The results present dual-connectivity as an optimal solution to ensure ultra high reliability and low signalling overhead. Another parameter, which achieve gains in both of reliability and signalling overhead, is high frequency band due to its high bandwidth which ensures higher user bandwidth that overcomes the degradation in combined SINR, due to its frequency band-based high pathloss.

ACKNOWLEDGEMENT

This work was in part supported by the Federal Ministry of Education and Research of the Federal Republic of Germany (BMBF) within the initiative “Region Zwanzig20” under project numbers 03ZZ0528E (”fast robotics”) and 03ZZ0510F (“fast automation”). This research was co-financed by public funding of the state of Saxony/Germany.

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APPENDIX

A. Derivations of Outage Probability

The outage probability in MC at position $(x,\,y)$ is

$$P_{\text{out}}\left(x,\,y\right)=\Pr\left(\Gamma^{\text{MRC}}\left(x,\,y\right)<\Gamma_{\text{th}}\right) \tag{20}$$

by including all links and the shadowing effect (only on the nearest APs)

$$P_{\text{out}}\left(x,\,y\right)=\Pr\left(\Gamma_k\left(x,\,y\right)e^{v}+\Gamma_{k+1}\left(x,\,y\right)e^{w}<\overline{\Gamma_{\text{th}}}\left(x,\,y\right)\right), \tag{21}$$

where

$$v,\,w\sim\mathcal{N}\left(0,\,\sigma_S^2\right)$$

, and

$$\overline{\Gamma_{\text{th}}}\left(x,\,y\right)=\Gamma_{\text{th}}-\sum_{i\in\mathcal{S}_n\setminus\{k,\,k+1\}}\frac{P_{\mathcal{A}}G_A\Theta_i\left(x,\,y\right)}{\sigma_N^2+\sum_{j\in\mathcal{I}_n}P_{\mathcal{A}}G_A\Theta_j\left(x,\,y\right)}.$$

$$P_{\text{out}}\left(x,\,y\right)=\Pr\left(v<d\left(k,w,x,y\right)\right), \tag{22}$$

$$d\left(k,w,x,y\right)=\log\left(\frac{\overline{\Gamma_{\text{th}}}\left(x,\,y\right)-\Gamma_{k+1}\left(x,\,y\right)e^{w}}{\Gamma_k\left(x,\,y\right)}\right).$$

Thus, the outage probability at position $(x,\,y)$ is:

$$P_{\text{out}}\left(x,\,y\right)=\int_{-\infty}^{z}\left(1-\mathcal{Q}\left(\frac{1}{\sigma_S}d\left(k,w,x,y\right)\right)\right)f\left(w\right)\,\partial w, \tag{23}$$

where $f\left(w\right)$ is pdf of shadowing in dB:

$$f\left(w\right)=\frac{1}{\sqrt{2\pi}\sigma_S}\exp\left(\frac{-w^2}{2\sigma_S^2}\right).$$

and

$$z=\log\left(\frac{\overline{\Gamma_{\text{th}}}\left(x,\,y\right)}{\Gamma_{k+1}\left(x,\,y\right)}\right).$$

Averaging (23) over uniform random variables x and y achieves the overall outage probability P_{out} in (12).

B. Derivations of Probability of Link Management

1) Probability of handover P_{LH}^{k}: Probability of handover in kth link at (x,y) is

$$P_{\text{LH}}^{k}\left(x,\,y\right)=\Pr\left(\Gamma_k(x,\,y)e^{v}<\Gamma_o(x,\,y)e^{w}-\mathcal{H}_s\right). \tag{24}$$

$$P_{\text{LH}}^{k}\left(x,\,y\right)=\Pr\left(v<\log\left(\frac{\Gamma_o(x,\,y)e^{w}-\mathcal{H}_s}{\Gamma_k(x,\,y)}\right)\right). \tag{25}$$

$$P_{\text{LH}}^{k}\left(x,\,y\right)=\int_{-\infty}^{g}\left(1-\mathcal{Q}\left(\frac{1}{\sigma_S}h(k,o,w,x,y)\right)\right)f\left(w\right)\,\partial w, \tag{26}$$

where

$$g=\log\left(\frac{\mathcal{H}_s}{\Gamma_o(x,\,y)}\right).$$

and

$$h(k,o,w,x,y)=\log\left(\frac{\Gamma_o(x,\,y)e^{w}-\mathcal{H}_s}{\Gamma_k(x,\,y)}\right).$$

Thus, probability of handover in all links is

$$P_{\text{LH}}\left(x,\,y\right)=1-\prod_{k\in K}\left(1-P_{\text{LH}}^{k}\left(x,\,y\right)\right). \tag{27}$$

2) Probability of adding link: Probability of adding link is

$$P_{\text{LA}}\left(x,\,y\right)=\Pr\left(\Gamma^{\text{MRC}}\left(x,\,y\right)\leq\Gamma_{\text{th}}\right). \tag{28}$$

By simplifying P_{LA} in similar way to (20), it become

$$P_{\text{LA}}\left(x,\,y\right)=P_{\text{out}}(x,\,y). \tag{29}$$

3) Probability of link drop P_{LD}: Probability of dropping link is joint probability of $\Pr\left(\Gamma_{\text{MRC}}>\Gamma_{\text{th}}\right)$ and probability of number of non-dropped links above threshold $\Pr\left(K>K_{min}\right)$

$$P_{\text{LD}}(x,\,y)=\Pr\left(\Gamma_{\text{MRC}}(x,\,y)>\Gamma_{\text{th}}\right)\cdot\Pr\left(K>K_{min}\right), \tag{30}$$

where

$$K_{min}=\begin{cases}1 & \text{if } K=2\\ 2 & \text{if } K>2,\end{cases}$$

$$\Pr\left(K>K_{min}\right)=\Pr\left(K\right)=\frac{K-K_{min}}{K_{min}}, \tag{31}$$

$$\Pr\left(\Gamma_{\text{MRC}}(x,\,y)>\Gamma_{\text{th}}\right)=$$

$$\Pr\left(\Gamma_k\left(x,\,y\right)e^{v}+\Gamma_{k+1}\left(x,\,y\right)e^{w}>\overline{\Gamma_{\text{th}}}\left(x,\,y\right)\right). \tag{32}$$

$$P_{\text{LD}}(x,\,y)=\Pr\left(v>d\left(k,w,x,y\right)\right)\cdot\Pr\left(K\right). \tag{33}$$

$$P_{\text{LD}}(x,\,y)=\Pr\left(K\right)\int_{z}^{\infty}\mathcal{Q}\left(\frac{1}{\sigma_S}d\left(k,w,x,y\right)\right)f\left(w\right)\,\partial w. \tag{34}$$

Thus, the probability of link management at position $(x,\,y)$ is

$$P_{\text{LM}}(x,\,y)=1-\left(\overline{P_{\text{LH}}(x,\,y)}\cdot\overline{P_{\text{LD}}(x,\,y)}\cdot\overline{P_{\text{LA}}(x,\,y)}\right), \tag{35}$$

where $\overline{P(x,\,y)}$ is the compliment of $P(x,\,y)$.

Averaging (35) over uniform random variables x and y achieves the overall probability of link management P_{LM} in (13).