Multi-Connectivity Management for Mobile Ultra-Reliable Low-Latency Communications

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***Abstract*—Recent mission critical wireless applications, such as emergency stop and safety application protocols (e.g., PROFIsafe), require ultra-reliable low-latency communications (URLLC) technologies to ensure error-free message transmission with hard real-time requirements. Multi-connectivity (MC) has emerged as a promising approach to enable URLLC in 5G. Applying MC in mobile communications poses multiple technical challenges, such as advanced handover (HO) schemes handling multiple links in parallel, highly dynamic link optimization, avoiding massive link drops due to fading and shadowing, and optimizing radio resource allocation/consumption. To address these challenges we propose an MC management scheme based on maximum ratio combining (MRC) for mobile communications in industrial scenarios. We compare the performance with existing HO schemes for Rayleigh fading channel conditions using extensive simulations. Compared to existing approaches, the results show improvements in achievable signal to noise ratio, link utilization, data rate, and availability.**

***Index Terms*—Multi-connectivity, URLLC, handover, maximum ratio combining, link management.**

I. Introduction

Upcoming wireless applications in industrial fields with, e.g., closed-loop control of mission critical tasks, require highly reliable, deterministic and low latency communications to meet safety and accuracy requirements [1]. However, in industrial environments, radio links experience strong link degradation and high outage probabilities due to fading channels and line-of-sight (LoS) path blockage [2]. To achieve highly reliable connectivity, the concept of inter-frequency multi-connectivity (MC) can significantly reduce the outage probability by exploiting space and frequency diversity. Implementing diversity combining schemes, such as maximum ratio combining (MRC) at the receiver side, improves the reliability and increase the quality of service (QoS) by orders of magnitude [3].

User mobility throughout the coverage areas of different access points (APs) requires handover (HO). Applying conventional HO schemes (i.e., link-based HO) to MC, multiple simultaneous HOs can occur causing "hard" handovers, inefficient resource utilization, etc. with negative impacts on communication reliability.

Different works have recognized this issue and tried to solve it. In [4], [5], a HO method for fast cell selection is proposed based on simultaneous connections to multiple APs in proximity. However, such a greedy scheme consumes many resources and affects network capacity. For inter-frequency HO decisions, the authors in [6]–[9] studied the impacts of different criteria, such as received signal strength (RSS), speed of mobile users, interference, energy, and developed a cost function combining these criteria. However, they considered single links in a two-tier macro-cell and femto-cell deployment. The authors in [10] studied the impact of different factors, such as user speed, placement of access points, Time-To-Trigger (TTT), user location, time of day, and antenna types using a dual-link on the soft-HO process in WLAN. These factors are used for short-term periodic prediction of cell selection. In addition, the authors in [11] proposed seamless dual-link HO for high-speed rail applications including a detailed study of signaling overhead. In [12], the effect of dual-connectivity on scheduling and cell association among macro and micro cells is investigated for LTE with carrier aggregation. Although different HO schemes have been studied for MC, many aspects have not been investigated, such as reliability degradation and inefficient resource utilization, which influence communication performance.

This paper studies mobility management aspects in the context of mobile URLLC in industrial environments using MC. The key contributions are as follows:

- We explore the shortcomings of recent HO solutions with respect to link utilization and reliability.
- We introduce a heuristic HO-scheme for MC which centrally optimizes the number of resources from the system perspective in order to fulfill the reliability constraints.
- The performance of the proposed algorithm is investigated and compared to literature, in terms of achievable SNR, throughput, link utilization, and system availability.

The rest of the paper is organized as follows: Section II describes the system model and problem formulation. The proposed algorithms for HO and admission control for the MC scheme are explained in Section III. Section IV describes the simulation scenario and discusses the results. Finally, section V summarizes this work.

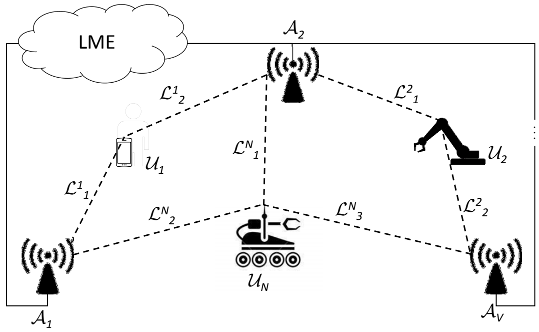

Fig. 1. Model of an industrial hall with AP deployment to serve users with MC.

II. System Model And Problem Formulation

This section introduces our system model for industrial wireless communications. Then, the problem of current solutions is formulated and the shortcomings are presented.

A. System Model

In this work, we consider a system model for the industrial hall depicted in Fig. 1, which includes a set of distributed APs throughout the building, denoted by $\mathcal{A}_v, v \in \{1, 2, \dots, V\}$, and a set of mobile users, denoted by $\mathcal{U}_n, n \in \{1, 2, \dots, N\}$. We consider Rayleigh fading channels with unit average channel gain and each link undergoes an independent fading process. In addition, shadowing $\mathcal{S}$ with log-normal distribution is considered in the industry hall resulting from the presence of obstacles [2].

Multi-connectivity (MC) is considered in the downlink, where multiple APs transmit a packet to user $\mathcal{U}_n$ on different frequency resources. Upon reception, user $\mathcal{U}_n$ then combines the packets using MRC. Correspondingly, each user $\mathcal{U}_n$ is equipped with M radio receiver branches to combine the received packets from up to M connected APs and therefore has a set $\mathcal{L}^n = \{\mathcal{L}_1^n, \mathcal{L}_2^n, \dots, \mathcal{L}_K^n\}$ of simultaneous links with cardinality $|\mathcal{L}^n| = K \le M$. It is assumed that the channel coefficients are independent and identically distributed (iid), which provides maximum diversity.

At user $\mathcal{U}_n$, the received SNR from AP $\mathcal{A}_v$ over link $\mathcal{L}_k^n$ is given as

$$\Gamma_k^n = \frac{PGd_{n-v}^{-\alpha} \left|h_k^v\right|^2 e^{\mathcal{S}}}{\sigma_n^2}, \tag{1}$$

where P is the transmit power of AP $\mathcal{A}_v$, G is the gain of transmit- and receive-antennas, d_{n-v} is the distance to AP $\mathcal{A}_v$, α is the pathloss exponent, h_k^v is the channel coefficient between AP $\mathcal{A}_v$ and user $\mathcal{U}_n$ on the k-th link, $e^{\mathcal{S}}$ is the shadowing effect, and σ_n^2 is the noise power on link $\mathcal{L}_k^n$ (assuming σ_n^2 is equal for all links). The total received SNR after MRC combining is [3]

$$\Gamma_{\text{MRC}}^n = \sum_{k \in K} \Gamma_k^n. \tag{2}$$

When mobile, user $\mathcal{U}_n$ experiences variation of Γ_k^n and different handover events could be triggered for each link [13]. We can distinguish three phases for each link: the SNR of the serving AP becomes worse than a threshold; the SNR to a neighboring AP becomes an offset better than the serving AP; and the SNR to the neighboring AP becomes better than the threshold. To perform HO efficiently and seamlessly, a Link Management Entity (LME) is required. It monitors Γ_k to trigger the appropriate action (add link, drop link, switch link). In addition, the LME is responsible for selecting the proper modulation scheme based on Γ_{MRC} to ensure high data rate and high reliablility.

B. Problem Formulation

MC has been presented in literature as a promising scheme to realize URLLC [3], [14]. However, link optimization has not been investigated to the best of our knowledge. In this paper, an LME is proposed to optimize the total number of links allocated to all users. Hence, the problem can be formulated as

$$\min \sum_{n=1}^{N} |\mathcal{L}^n|, \tag{3a}$$

$$\text{s. t.} \quad |\mathcal{L}^n| \le M \quad \forall n \in \{1,2,\dots,N\}, \tag{3b}$$

$$\Gamma_{\text{MRC}}^n \ge \Gamma_{\text{th}} \quad \forall n \in \{1,2,\dots,N\}. \tag{3c}$$

Solving such a problem requires a centralized control unit which continuously optimizes the total number of links for all users. In recent technologies, optimizing the number of links in MC is done using heuristic schemes based on conventional handover (CoHO) for each user $\mathcal{U}_n$ individually. 3GPP specifies the following handover events to be considered: [4], [5], [13]

$$\text{A2}: \quad \Gamma_k^n \le \max_{k \in K} \Gamma_k^n - \Gamma_{\text{D}}, \quad \text{(Drop link)} \tag{4a}$$

$$\text{A3}: \quad \Gamma_k^n + \mathcal{H}_s \le \Gamma_o \quad \text{(Switch link)} \tag{4b}$$

$$\text{A4}: \quad \Gamma_p \ge \max_{k \in K} \Gamma_k^n - \Gamma_{\text{A}}, \quad \text{(Add link)}, \tag{4c}$$

where Γ_{A} and Γ_{D} are offset windows for adding and dropping links, $\mathcal{H}_s$ is the hysteresis, and Γ_p is the SNR of o-th link to the non-serving AP $\mathcal{A}_p$ in proximity. To avoid ping-pong/bouncing effects, there should be an offset q between Γ_A and Γ_D (i.e., $\Gamma_D = \Gamma_A + q$). Hence, dropping the k-th link can only occur if its Γ_k is severly degraded [5].

The CoHO pushes the system toward increasing individual number of links to maximize Γ_{MRC} through the addition (and retention) of every high-SNR link. Thus, the CoHO is in conflict with the optimization problem in (3) and the whole system will have inefficient resource utilization. In the next section, we introduce a heuristic HO-scheme for MC to overcome this problem.

III. Proposed Solution: Link Management Algorithm (LMA)

Improving the reliability of communications in industrial environments necessitates optimizing the number of assigned links per user to improve system capacity and performance stability. By applying MC, an appropriate criterion is required to adapt the number of concurrent links to different APs. This criterion should reflect the instantaneous performance of communication over different links and meet the optimization goal in (3).

In this paper, a new heuristic scheme for handover in MC is proposed, which is called link management algorithm (LMA). This algorithm uses Γ_{MRC} as a metric for communication performance to manage $\mathcal{L}_n$ with Γ_{L} as a minimum reliability requirement as follows:

$$\min_{k \in M} \sum_{k=1}^{M} \Gamma_k^n, \tag{5a}$$

$$\text{s. t.} \quad \Gamma_{\text{MRC}}^n \geq \Gamma_{\text{L}} \geq \Gamma_{\text{th}}, \tag{5b}$$

where Γ_{L} is the minimum SNR. To meet such a constraint, LMA should optimize $|\mathcal{L}^n|$ based on the minimum required SNR to meet QoS targets.

The proposed LMA has three different actions:

- **Add Link** from non-connected APs, which is triggered only if Γ_{MRC}^n is less than the minimum combined SNR Γ_{L}^n. The additional links $\mathcal{L}_a^n$ become a subset of $\mathcal{L}^n$ ($\mathcal{L}^n \leftarrow \mathcal{L}^n \cup \mathcal{L}_a^n$),
- **Drop Link** to an AP, which is triggered only if Γ_{MRC}^n exceeds the minimum combined SNR Γ_{L}^n. The weakest link can be dropped, if the combined SNR of the remaining links is still higher than the required threshold. The minimum number of remaining links is assumed to be 2 ($\mathcal{L}_d^n \not\subset \mathcal{L}^n, |\mathcal{L}^n| \geq 2$).
- **Switch Link** triggers switching of links between serving AP $\mathcal{L}_k$ and neighbor AP $\mathcal{L}_o^n$ based on the A3 event in (4) without modifying $|\mathcal{L}^n|$.

Figure 2 shows the idea of the proposed LMA. The domain of Γ_{MRC}^n is divided into two regions (based on the algorithm's actions): "Add link" which covers the region below Γ_{L}; and "switch" and "drop link", which cover the region above Γ_{L}. The aim of these two regions is to keep Γ_{MRC}^n above Γ_{L} with the minimum number of links. The exact LMA is given in Algorithm 1.

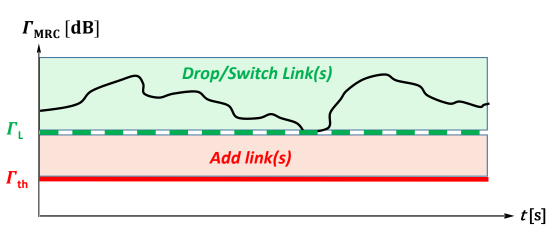

Fig. 2. LMA principle to maintain stable SNR Γ_{MRC} while facing mobility.

Algorithm 1 LMA algorithm for HO in MC scheme

procedure LMA(*RSS*,*M*)
  Measurement:
  Calculate Γ_k^n from neighbor APs
  Calculate Γ_{MRC}^n from Eq.2
  if $\Gamma_{\text{MRC}}^n \leq \Gamma_{\text{L}}$ **then**
    $\mathcal{L}_a^n = \arg\min_{v \in V} \sum_{v=1, v \notin \mathcal{L}^n}^{V} \Gamma_v^n$ ▷ Select Links
    $\mathcal{L}^n \leftarrow \mathcal{L}^n \cup \mathcal{L}_a^n$ ▷ Add link(s)
  else if $\Gamma_{\text{MRC}}^n \geq \Gamma_{\text{L}}$ **then**
    $\mathcal{L}_d^n = \arg\min_{k \in K} \sum_{k=1}^{K} \Gamma_k^n$ ▷ Select Links
    $\mathcal{L}_d^n \not\subset \mathcal{L}^n$ ▷ Drop link(s)
    if $\Gamma_k^n < \Gamma_v^n - \mathcal{H}_s$ **then**
      $\mathcal{L}_o^n \in \mathcal{L}^n, \quad \mathcal{L}_k \notin \mathcal{L}^n$ ▷ Switch Links
    end if
  end if
  go to *Measurement* ▷ Meet (5)
end procedure

In addition to LMA, the LME is responsible for link adaptation based on Γ_{MRC}. Selecting the proper modulation and coding scheme (MCS) q, which achieves data rate R_b with a certain reliability (e.g., given as packet error rate (PER) for Γ_{th}). R_b is computed based on the MCS and the payload [15]:

$$R_b = \frac{\mathcal{B}}{\mathcal{T}}, \tag{6}$$

where $\mathcal{B}$ is the payload (in bits), $\mathcal{T}$ is the packet transmission time based on preamble duration t_ρ (40 s), OFDM symbol duration time t_s (4 μs), number of sub-carriers N_{sc}, and applied number of bits per symbol b_s

$$\mathcal{T} = t_\rho + t_s \cdot \left(\frac{\mathcal{B}}{b_s \cdot N_{sc}} \right). \tag{7}$$

Table I shows the required SNR's Γ_{MRC} range to achieve a reliability of $1 - 10^{-6}$ using different modulation schemes q, and different bit rates R_b for IEEE 802.11ac with $N_{sc} = 52$ sub-carriers [16].

TABLE I
LINK ADAPTATION AND EQUIVALENT q, R_b

Decision range	q	R_b (Mbps)
$15 < \Gamma_{\text{MRC}}^n \leq 16$	BPSK	9.7
$16 < \Gamma_{\text{MRC}}^n \leq 23$	QPSK	15.38
$23 < \Gamma_{\text{MRC}}^n \leq 29$	16-QAM	22.2
$29 < \Gamma_{\text{MRC}}^n$	64-QAM	25

IV. Simulation Results

To study the performance of our LMA and compare it to literature, a scenario for an industrial hall with hexagonal AP deployment is simulated, as shown in Fig. 3. A user $\mathcal{U}_1$ is connected via multiple links to perform different applications (such as augmented reality, remote

TABLE II
SIMULATION ASSUMPTIONS

	Parameter	Value
Setup	Dimensions $(L \times W)$ [m]	120 × 120
	MN speed [m/s]	5
	Access point height [m]	6
	Distance between APs [m]	15
	User device height [m]	1.5
Configuration	Number of receiver branches M	6
	Antenna gain G [dBi]	3
	Channel bandwidth [MHz]	20
	Operating frequency range [GHz]	[5.17, 5.25]
	Target outage ε	10^{-6}
	Communication type	FDD
	Modulation scheme q	BPSK,QPSK, 16-QAM, 64-QAM
Channel	Path loss exponent α	2.59
	Shadowing [dB]	$\mathcal{N}(0, 6.09)$
	Fast fading	Rayleigh fading
	Path Delay coefficient $(\times 10^{-7})$	$\{0, 2, 5, 10, 16\}$
	Average path gain coefficient	{0, -3, -10, -20, -30}
	Doppler shift [Hz]	86.67
	Noise power density N_0 [dBm/1 MHz]	-110
	Noise figure NF [dB]	9
Simulation	threshold SNR Γ_{th}	13
	lower bound SNR Γ_{L} [dB]	15
	Simulation time step Ts [ms]	10
	Simulation time T [s]	120
	Time-To-Trigger (TTT) [ms]	50
	Diversity order	5
	Receiver sensitivity [dBm]	-87
	Packet size [Byte]	200
	SNR offset q	3 dB
	SNR link drop offset Γ_D	9 dB

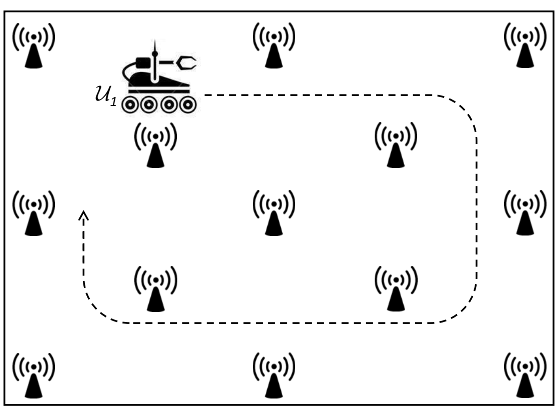

Fig. 3. Industrial hall with hexagonal deployment of 13 APs and a mobile robot.

control, etc.) and moves on a rectangular path with dimension (80 × 80) m with a speed of 5 m/s.

Two different HO schemes are considered: i) the proposed scheme (LMA); and ii) a Fast cell selection scheme (CoHO), as proposed in [5]. All simulation assumptions and parameters are summarized in Table II. Based on [5], we choose the SNR offset for adding and dropping Γ_A links as 6 and 9 dB, respectively.

To evaluate the performance of LMA, five different Key Performance Indicators (KPIs) are investigated for a fair comparison between LMA and CoHO schemes: i) received SNR Γ_{MRC}; ii) instantaneous PER P_e; iii) data rate R_b; iv) link utilization ζ_R; and v) system availability A.

A. Received Signal-to-Noise Ratio

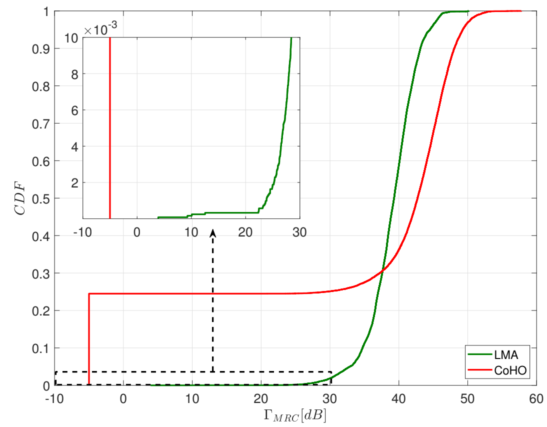

Fig. 4. CDF of combined SNR Γ_{MRC} using different HO schemes (LMA and CoHO).

Figure 4 shows the cumulative density function (CDF) of Γ_{MRC} using both HO schemes (LMA and CoHO). The proposed scheme outperforms CoHO below $\Gamma_{\text{MRC}} \leq 38$ dB. This is the result of the strategy for optimizing links in case of degradation of Γ_{MRC} based on the constraints in (5): CoHO adds links based on Γ_b from a neighboring AP with Γ_{A} in (4). This condition can frequently not be fulfilled due to fading and shadowing. On the other hand, above $\Gamma_{\text{MRC}} = 38$ dB CoHO outperforms LMA as it is frequently adding high quality links, as in (4). However, this improvement by CoHO utilizes a high number of links $|\mathcal{L}^n|$ (greedy behavior). These SNR improvements in the high-SNR regime are not very beneficial for the application and come at the cost of high resource consumption.

B. Data Rate

The data rate R_b is adapted during transmission based on the SNR Γ_{MRC} as given in Table I. In turn, the Γ_{MRC} is influenced by fading, shadowing and the number of links. The percentile of the achievable throughput values $\mathcal{C}_a$ reflects the percentage of achievable throughput during simulation time.

Figure 5 shows the percentile of achievable throughput $\mathcal{C}_a$ for LMA and CoHO. The LMA scheme achieves $\mathcal{C}_a$ of 97% for $R_b = 25$ Mbps, compared to 74% using the CoHO scheme. The main reason behind this improvement is the possibility to add links without restriction of Γ_{A}, as in CoHO. At the absence of strong links from neighboring cells, multiple weak links can improve Γ_{MRC} to maximize R_b. This improvement reduces the

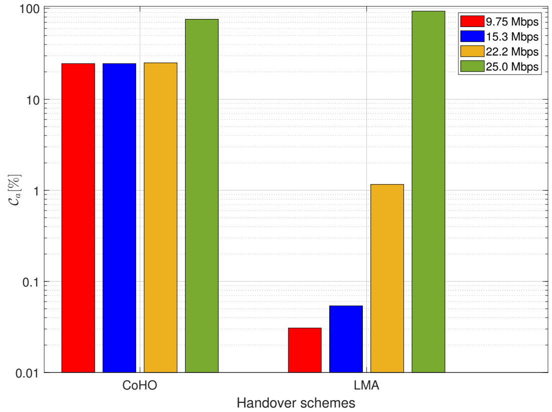

Fig. 5. Percentile of achievable throughput $\mathcal{C}_a$ for different throughput R_b values and HO schemes (LMA and CoHO).

probability of low rates R_b (9.75 Mbps) by 30% to 60%, compared to the CoHO scheme.

C. Link Utilization

To evaluate resource consumption during simulation time, we use link utilization as a metric. It is defined as

$$\zeta = \frac{t_K}{T}, \tag{8}$$

where t_K is the time where $K = |\mathcal{L}^n|$ links are assigned to user $\mathcal{U}_n$, and T is the simulation time.

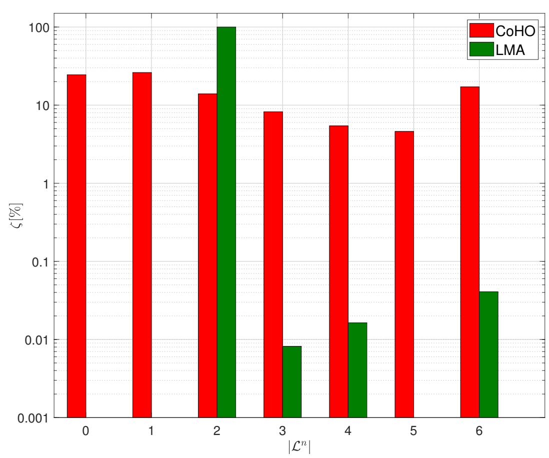

Fig. 6. Percentage of link utilization ζ for optimized link numbers $|\mathcal{L}^n|$ using LMA and CoHO. $|\mathcal{L}^n|$ of zero reflects low Γ_{MRC} ($< \Gamma_{\mathrm{th}}$) for $\mathcal{U}_1$.

Figure 6 shows ζ for different values of $|\mathcal{L}^n|$ using LMA and CoHO. LMA uses less $|\mathcal{L}^n|$ (more than 99% with $|\mathcal{L}^n|$=2) during simulation time, compared to CoHO, because it optimizes the number of links based on the constraints in (5). On the other side, LMA keeps assigning more than one resource to avoid low reliability. The CoHO scheme has more than 10% of ζ with zero $|\mathcal{L}^n|$ which indicates more than 10% of simulation time in outage, with no communication between users and APs.

D. System Availability

In addition to the aforementioned metrics, time-based performance metrics have been proposed to evaluate the operation life time of the system [17], [18]: i) mean time to failure (MTTF); ii) mean time to repair (MTTR); iii) mean time between failures (MTBF).

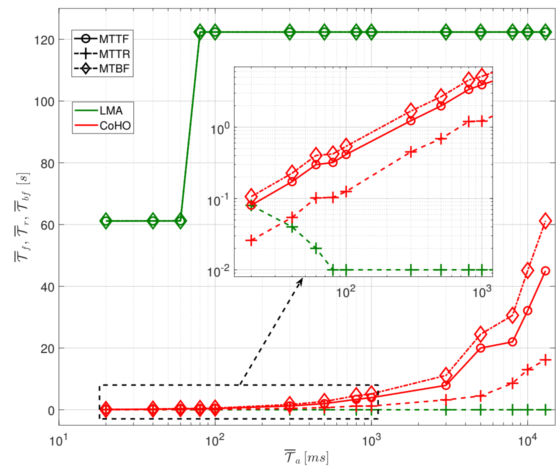

Fig. 7. MTTF $\overline{\mathcal{T}}_f$, MTTR $\overline{\mathcal{T}}_r$, and MTBF $\overline{\mathcal{T}}_{bf}$ vs message arrival time $\overline{\mathcal{T}}_a$ using different HO schemes in MC.

Figure 7 shows MTTF $\overline{\mathcal{T}}_f$, MTTR $\overline{\mathcal{T}}_r$, and MTBF $\overline{\mathcal{T}}_{bf}$ versus different message inter-arrival times $\overline{\mathcal{T}}_a$ using both handover schemes. LMA achieves a stable $\overline{\mathcal{T}}_f$ and $\overline{\mathcal{T}}_r$, compared to CoHO. This improvement is due to shifting the received SNR Γ_{MRC} to a region above Γ_{th} and hence, decreasing link failure probability. Increasing $\overline{\mathcal{T}}_a$ reduces transmission frequency and thus probability of transmission during "OFF" time frames. Hence, it increases $\overline{\mathcal{T}}_f$ and decreases $\overline{\mathcal{T}}_r$. However, higher $\overline{\mathcal{T}}_a$ values do not influence $\overline{\mathcal{T}}_f$, $\overline{\mathcal{T}}_r$, and $\overline{\mathcal{T}}_{bf}$. By using CoHO, increasing $\overline{\mathcal{T}}_a$ increases both $\overline{\mathcal{T}}_f$ and $\overline{\mathcal{T}}_r$ in exponential fashion. This is due to low SNR Γ_{MRC} (below Γ_{th}) which increases the probability of link drop and thus increases "OFF" time, regardless of increasing $\overline{\mathcal{T}}_a$.

The availability of the system based on MTTF and MTTR is

$$A = \frac{\overline{\mathcal{T}}_f}{\overline{\mathcal{T}}_f + \overline{\mathcal{T}}_r}. \tag{9}$$

Figure 8 shows the availability A of the system for different message inter-arrival times $\overline{\mathcal{T}}_a$ using both handover schemes. LMA shows stable high availability A, compared to CoHO. This is due to high $\overline{\mathcal{T}}_f$ and low $\overline{\mathcal{T}}_r$ by increasing $\overline{\mathcal{T}}_a$, which stabilize A. For the CoHO scheme, increasing $\overline{\mathcal{T}}_a$ increases both $\overline{\mathcal{T}}_f$ and $\overline{\mathcal{T}}_r$. The variance of A using CoHO is caused by the variance in difference between $\overline{\mathcal{T}}_f$ and $\overline{\mathcal{T}}_r$.

V. Conclusion

In this paper, a new HO scheme for MC is proposed to realize URLLC in a mobile industrial setting. The

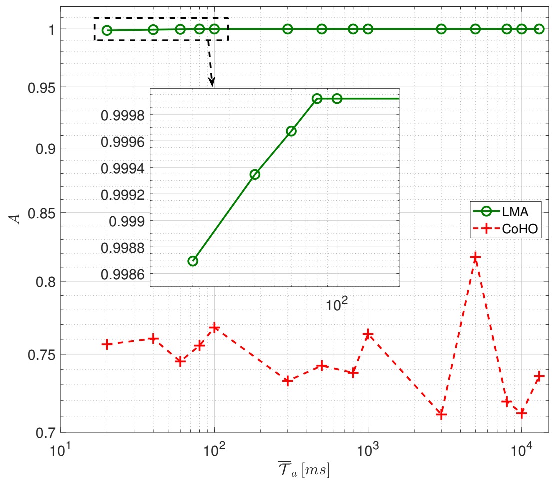

Fig. 8. Availability A vs message arrival time $\overline{\mathcal{T}}_a$ using different HO schemes in MC.

proposed scheme optimizes the number of links based on QoS requirements and the dynamic radio environment. The results show that the proposed HO scheme can achieve low resource utilization, stable instantaneous SNR, high availability, and high data rate, compared to conventional approaches. Future work will focus on adapting the proposed HO algorithm to tactile connected driving in vehicular communication and integrate it with radio resource management approaches.

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