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INCREASING SAFETY LEVELS IN HUMAN-MACHINE INTERACTION BY BEYOND-5G WIRELESS REDUNDANCY

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Abstract *– Factory automation in the context of Industry 4.0/5.0 requires safety levels to satisfy more stringent and tight limits than those available so far. This goal is further challenged by the extension to the wireless environment of industrial shop floor communications that were traditionally based on cabled networks. Starting with wireless LANs, the trend towards the use of industrial wireless is fostered by the advent of fifth Generation (5G) private connectivity and is bound to increase its pace in the evolution towards 6G. In particular, the interaction of human operators with industrial robots and autonomous vehicles on the shop floor is posing stringent safety requirements that in turn push forward the dependability and reliability limits of wireless connectivity. To help achieve these limits, this paper proposes a dynamic redundancy mechanism based on the real-time activation/deactivation of radio bearers instantiated between mobile devices carried by humans and machines and multiple base stations, to achieve guaranteed upper bounds on packet loss probability in the communication of data related to operational safety control loops. An optimization problem is posed, and suitable heuristics are evaluated by simulation in a 5G and beyond wireless environment, aiming to dynamically maintain the required reliability levels with small computational effort.*

Keywords – Beyond 5G, human-robot collaboration, Industry 4.0/5.0, reliability

1. INTRODUCTION

Automation processes in industrial environments pose stringent requirements in the presence of moving robots and vehicles on the shop floor, to avoid accidents and to increase the level of safe Human-Robot Collaboration (HRC). This concern applies to both heavy-duty industrial robots with load capacities beyond 35 kg, that still represent a significant challenge for safe unfenced human-robot interaction in assembly lines (see, e.g., ISO Technical Specifications [1]-[3]), owing to the specific robot features (weight, range, speed, etc.), and to Unmanned Autonomous Vehicles (UAVs) or Automated Guided Vehicles (AGVs). In this context, while Industry 4.0 focuses on the technical aspects around Cyber-Physical Systems (CPSs), the concept of Industry 5.0, as defined, e.g., by the European Commission [4], "…provides a vision of industry that aims beyond efficiency and productivity as the sole goals, and reinforces the role and the contribution of industry to society", involving a more human-centric vision through individualized Human-Machine Interaction (HMI), data transmission, storage and analysis technologies, and Artificial Intelligence/Machine Learning (AI/ML), among other enabling technologies [5]. This vision further enhances the relevance of wireless connectivity in industrial environments to foster safe HRC.

Traditionally, industrial communications have been centred on the use of specific local network architectures for the interconnection of specialized components and applications, like Programmable Logic Controllers (PLCs), Supervisory Control and Data Acquisition (SCADA) systems and Distributed Control Systems (DCSc); these network architectures have gradually evolved from field buses to industrial Ethernet solutions and, more recently, to Wireless LAN (WLAN) technologies [6]. The latter may need some enhancements to meet the strict requirements of the industrial environment in terms of Quality of Service (QoS) and reliability; see, e.g., [7]-[10].

With the advent of 5G, industrial applications over private 5G wireless networks are starting to appear. A recent example is constituted by the use cases being implemented in the framework of the 5G-

INDUCE H2020 5G PPP European Project (Open cooperative 5G experimentation platforms for the industrial sector NetApps) [11], which is developing eight vertical network application use cases in the industrial environment to be experimented over three different 5G facilities; in particular, one of these use cases relates specifically to collision avoidance between forklifts and human operators at crossroad blind spots on the factory floor. Thus, a relevant aspect to be further investigated that is pushing 5G beyond its nowadays provided capabilities is represented by the extreme reliability levels. This is a requirement of many critical applications emerging in advanced smart scenarios [12], among which HRC ones are particularly challenging. Indeed, the customization and flexibility trends in the manufacturing industry are leading to closer contact between robots and workers, which has raised security aspects to a top priority for HRC, still predominating in the automotive and electronics industry. In particular, humans and heavy-payload robots are required to work at shorter safety distances. In such a context, it is thus important that they are provided with easy-to-integrate functional-safe systems that ensure both human safety and flexible use in existing and future assembly lines. Specifically, the detection of possible collision courses in real time and the automated machinery control for run-time human collision avoidance would imply the satisfaction of strict latency constraints [13], [14] and extremely high reliability levels. Enhancing reliability in this kind of industrial manufacturing environment has been exactly the goal of the already cited works [7]-[10], by replicating messages over multiple independent channels in the WiFi context, along the line suggested by the Parallel Redundancy Protocol (PRP) specified in the IEC 62439-3 standard (see [15] for the latest edition).

In this paper, we continue this line of reasoning and extend it to 5G (and beyond) wireless networking, by expanding the approach already initiated in our previous work [16]. We believe that the opportunities offered by the activation of more than one bearer per User Equipment (UE) in the redundant transmission for a high reliability communication feature introduced by 3GPP [17], if enhanced with the possibility of multiple (>2) additional instantiations in the future releases, together with the Ultra-Reliable Low-Latency Communication (URLLC) service category [18], can greatly improve the communication efficiency limits of the HRC scenario.

In [16] we have presented the first results obtained by a software simulator to evaluate the performance of an ad hoc algorithm for adaptive instantiation/de-instantiation of multiple bearers, in the presence of several 5G base stations (gNodeBs – gNBs) deployed across the shop floor in an industrial environment characterized by the presence of moving human operators and robots. The extension we present here is twofold: first, we formalize the problem of maintaining packet loss below a certain desired threshold with the minimum possible number of parallel redundant bearers per involved UE, under all environmental impairments affecting the wireless channels, as a variant of a multi-assignment problem [19]; then, we present a refinement of the heuristic algorithm already considered in [16], whose main goal is to allow dynamic network reconfiguration to keep the desired reliability levels in real time, along with new simulation results.

The paper is organized as follows. In Section 2 we further detail the problem of collision avoidance in HRC. We formally introduce the optimization problem and describe a suitable heuristic algorithm in Section 3. Simulation results and conclusions are presented in sections 4 and 5, respectively.

2. CONSIDERED SCENARIO FOR HUMAN-ROBOT INTERACTION

The industrial shop floor is characterized by a harsh electromagnetic environment, where multiple obstacles tend to impair the propagation of electromagnetic waves, by creating absorption and reflection phenomena [20].

Regarding 5G, besides the innovations in the wireless segment, a characteristic feature from the networking point of view is the tighter integration between wireless and access/backhaul/core segments, as well as the increased presence and relevance of mobile edge computing to properly support vertical applications. As already mentioned in the Introduction, reliability is of fundamental relevance in the industrial environment; in terms of communications, it is closely related to the packet loss rate, which for URLLC must not go above 10^{-6} [18]. However, HRC has a reliability requirement of 10^{-7} [20] in terms of packet loss, but 5G currently can guarantee up to 10^{-4} [17]. The fulfilment of such extreme requirements, on the other hand, should not put a heavy toll, in terms of signalling, on the control/management and monitoring of the network, even in the presence of large numbers of heterogeneous devices.

The redundant transmission for high reliability communication feature introduced by 3GPP [17], potentially extended to more than two Protocol Data Unit (PDU) sessions, can represent a promising tool in this respect. Obviously, a dynamic activation/deactivation of redundant bearers is necessary, in order to use additional resources whenever a collision course is detected, and to release them when the distance between human and robot is such that the probability of collisions becomes close to zero.

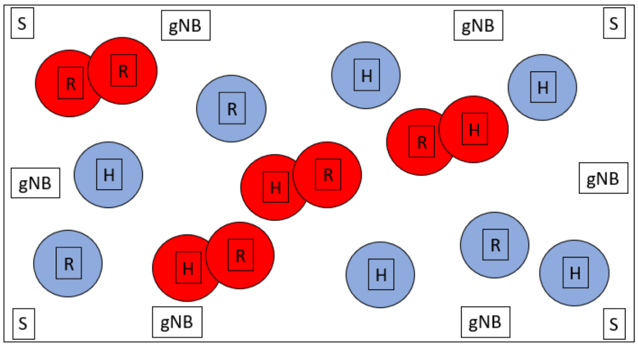

Fig. 1 – Scenario considered in our study. In the figure, gNB indicates gNodeB; robots and humans are denoted by R and H, respectively; generic sensors are denoted by S (as an example, only sensors deployed in the area, such as IP cameras, are depicted); critical areas are represented by the circles around both humans and robots. Red (blue) circles indicate that the corresponding UEs are (are not) in critical situations.

We consider an industrial area in which q agents work together and in general move to carry out their tasks. Specifically, $q = q_H + q_R$, where q_H denotes the number of humans and q_R the number of robots. Robots exploit IoT technologies to autonomously perform their work in a context-aware and accurate way, while feeding/receiving feedback from a control loop with the goal of ensuring the safety of humans. In this context, connectivity lets robots provide feedback to the control loop and the other way around. Since the knowledge of the distance between human and robot is of paramount importance, several detection devices can be placed on the robot (e.g., proximity sensors), on the area (e.g., sensors, IP cameras), and/or even on the human (e.g., smart glasses, smartphones, tablets, etc.). These devices transmit their signals to a set of 5G gNBs, positioned throughout the area to provide overall coverage. A generic representation of the scenario is shown in Fig. 1.

In order to avoid unnecessarily wasting resources, the reliability level must be commensurate with the likelihood of a collision, which in turn is driven by the distance between humans and robots. Specifically, we have introduced in [16] the concept of *adaptive reliability* to express the application of the most proper controls, as well as the gathering of the right amount of resources, related to the current situation.

In this respect, the goal of our work is to ensure a desired reliability level *adaptively* by introducing *seamless redundancy* [15], [7], and at the same time by distinguishing between critical and non-critical operating conditions, owing to the fact that enhanced reliability requires more bandwidth and implies less scalability. Thus, whenever a critical situation is perceived by one or more UEs, a decision needs to be taken for the choice of the minimum number of radio bearers to be instantiated to ensure the desired reliability level, as well as of the gNBs toward which to activate them. Then, multiple copies of each data packet carrying the information that will be necessary to perform the control actions to avoid the collisions would be transmitted in parallel over the selected bearers, so that at least one copy can reach the controller situated in the computational devices at the network edge with the desired probability.

It is worth noting that our problem formulation regarding the choice of bearers concerns only the activation of the proper communications resources and has no relation with the control law to be enforced to act on the collision course. However, since the communication and control task will act sequentially, we need to keep the former as fast as possible; namely, the final goal is to achieve sub-ms times.

3. ADAPTIVE RELIABILITY: DYNAMIC INSTANTIATION OF REDUNDANT BEARERS

We assume that the overall shop floor area can be ideally divided into subareas, and that data is either successfully transmitted or lost by any UE in each subarea to each gNB in accordance with a specific *loss probability*. Such loss probabilities, generally time-varying as they account for both the approximately static expected quality of signals and for sudden and limited-in-time interferences, can be pre-calculated in static operating conditions and continuously updated over longer time scales than those involved with a bearer's activation decisions.

The evaluations reported in Section 4 assume stationary conditions. Therefore, the current position of each UE, the gNBs towards which the UE is transmitting packets, and, consequently, the loss probability associated to such gNBs for the specific subarea of interest, will determine whether data transmission will be either successful or not.

3.1 General problem statement

Since establishing redundant channels requires the use of more resources, the redundancy mechanism is activated in order to achieve the desired reliability level, expressed in terms of an upper bound $\ell_{d,\text{critical}}$ on the overall loss probability of the redundant transmissions, only in critical situations, i.e., when the distance between humans and robots, or robots and robots, is below a predefined critical threshold r. Whenever it is detected that, at a certain time instant t, such distance $d_{i_s j_s}(t)$ between one or more pairs of UEs i_s and j_s , $s = 1,2, \ldots$, carried by a human and a robot, respectively, is falling below the critical value r, the estimated overall loss probability $\ell_{e,red}(t)$ achievable through redundancy is required to be less than or equal to a desired threshold $\ell_{d,\text{critical}}$, which we assume as a fixed design parameter. In normal operating conditions, the required upper bound on the packet loss level is allowed to be $\ell_d > \ell_{d,\text{critical}}$. On the other hand, since each bearer instantiation has a cost in terms of resources, the number of bearers for each UE should be kept as low as possible, while satisfying the requirement on $\ell_{e,red}(t)$. Moreover, it is important to note that the maximum benefit of the applied redundancy for a given UE would be obtained whenever the random effects characterizing the activated radio bearers could be considered independent, which would also allow us to express the overall loss probability as a product of those of the individual ones for each bearer.

The association of UEs in critical conditions to bearers can be stated as a variation of the previously mentioned multi-assignment problem. It is worth noting, however, that the solution involving multiple UE pairs simultaneously would be configured as an informationally centralized optimization problem among the pairs considered. To be implemented, this might require a considerable amount of signalling information to be exchanged on the UEs' reciprocal positions and on their PDU sessions with gNBs. After formalizing the optimization problem in this way, then, in the next section we will consider a decentralized version based on the problem seen individually by each human or robot-carried UE at the moment it detects a dangerous situation.

With regard to the decision timings, we assume each possible assignment and reconfiguration to be triggered by the above-mentioned critical distances, by considering the activation of additional bearers for those UEs, whose reciprocal distances go below the threshold, and their deactivation whenever the situation returns to normal operating conditions. For the sake of notational simplicity, from now on we will drop the index t in the problem formulation, unless strictly necessary for the clarity of the description.

We will assume that, for each UE i involved in the process, we can identify a subset of independent bearers $\mathcal{A}(i)$ toward a subset of gNBs. The mechanisms to perform such identification have been explicitly considered in [21]; here, we concentrate on the ensuing decision problem. Obviously, the UEs and gNBs involved, the corresponding bearers and the estimated loss probabilities can change at each triggering event, so that the optimization problem is time-varying. However, as the dynamics of the process of moving objects in the scene would be way much slower than the packets' generation and transmission times, we will consider successive decisions to be taken in a quasi-static situation and, therefore, all the relevant quantities will be defined without explicitly indicating the time index.

We adopt the superscript b to indicate bearers. Then, we define:

- $\mathcal{A}$, as the set of all possible UE-bearer pairs;
- $\mathcal{A}(i)$, as the set of independent bearers that can be associated to UE i;
- m, as the number of gNBs involved in the decision;
- q, as the number of UEs involved in the decision;
- $\overline{n}_j^b$, $j = 1 \ldots m$, as the maximum number of radio bearers that a specific gNB j is able to manage simultaneously;
- $\overline{N}_i^b$, $i = 1, \ldots, q$, as the maximum total number of radio bearers that a particular UE i can instantiate at the same time;
- $h = 1, \ldots, \overline{h} = \sum_{j=1}^{m} \overline{n}_j^b$, as the index of radio bearers (corresponding to interfaces at gNBs); we suppose $q < \overline{h}$; let also $h^{(j-1)} = \sum_{k=1}^{j-1} \overline{n}_k^b$, $j = 2, \ldots m$, and $h^{(0)} = 0$;
- ℓ_{ih}, as the loss probability experienced by UE i over bearer h;
- $x_{ih} = \begin{cases} 1 & \text{if UE } i \text{ is assigned to bearer } h \\ 0 & \text{otherwise} \end{cases}$;

Then, by following the notation adopted in [19], where the maximization of a benefit for the assignment is considered, the general assignment problem can be defined as follows:

$$\min \sum_{(i,h)\in\mathcal{A}} x_{ih} \tag{1}$$

subject to

$$\sum_{\substack{p=1 \\ (i,h_p)\in\mathcal{A}(i)}}^{\overline{N}_i^b} x_{ih_p} \geq 1 \quad , \quad i = 1, \dots, q \tag{2}$$

$$\sum_{i=1}^{q} x_{ih} = 1 \quad , \quad h = 1, \dots, \overline{h} \tag{3}$$

$$x_{ih} \in \{0,1\}, \qquad \forall (i,h) \in \mathcal{A} \tag{4}$$

Constraints (2)-(4) are the classic ones of the multi-assignment problem [19]. However, in our case, we should also add the constraints on the desired overall loss probability and on the maximum number of radio bearers that a gNB is allowed to activate. Regarding the former, we note that, owing to the independence assumption, the total loss can be written as a product of the loss probabilities of the chosen bearers; the product can be conveniently transformed into a sum by considering logarithms of the quantities involved. Therefore, we have the additional constraints:

$$\sum_{\substack{p=1 \\ (i,h_p)\in\mathcal{A}(i)}}^{\overline{N}_i^b} x_{ih_p} \cdot \log \ell_{ih_p} \leq \log \ell_{d,\mathrm{critical}} , \quad i = 1, \dots, q \tag{5}$$

$$\sum_{i=1}^{q} \sum_{h=h^{(j-1)}+1}^{h^{(j-1)}+\overline{n}_j^b} x_{ih} \leq \overline{n}_j^b \, , \quad j = 1, \dots, m \tag{6}$$

The rationale is to find the minimum number of bearers to be activated for each UE to keep the loss probability below the threshold, while respecting the constraints on the maximum number of bearers that can be handled per UE and per gNB.

3.2 Suboptimal solution

Algorithms belonging to the "auction" category that might be investigated for possible adaptation to this problem can be found in [19]. However, the presence of constraints (5) and (6) makes such adaptation not straightforward; moreover, the centralized problem outlined in the previous section may present scalability and computational time issues which are not compatible with the stringent requirements imposed by the specific industrial framework that we consider in this paper. Therefore, keeping in mind our previous observation on the exchange of signalling information and the fact that we want to achieve computational times compatible with real-time operation (ideally, in the order of the ms), we resort here to a refined version of the suboptimal approach that we already adopted in our previous conference paper [16].

To do so, we basically convert the problem into a quasi-decentralized optimization to be solved by each UE i, $i = 1,\cdots,q$, whenever a dangerous situation is perceived. In practice, we restrict the search for UE i to the set $\mathcal{A}(i)$ of possible gNB interfaces the UE is allowed to use to send different copies of the same packet. It is worth noting that, in doing so, the set $\mathcal{A}(i)$ is influenced dynamically by the selection of interfaces corresponding to bearers' activations made by other UEs simultaneously involved in critical situations. Let $n^{(i)} = |\mathcal{A}(i)|$, and $N_i^{b,k} \sqsubseteq \mathcal{A}(i)$ be the subset of gNB interfaces in the k-th combination among the possible ones, $k = 1, \dots, k_{max}^{(i)}$, $k_{max}^{(i)} = \sum_{h=1}^{\overline{N}_i^b} \binom{n^{(i)}}{h}$. Then, our goal is the following:

$$\min_{k\in\left\{1,\dots,k_{max}^{(i)}\right\}} \left|N_i^{b,k}\right| \tag{7}$$

subject to

$$\prod_{h_k\in N_i^{b,k}} \ell_{ih_k} \leq \ell_{d,\mathrm{critical}} \tag{8}$$

(or, equivalently, $\sum_{h_k\in N_i^{b,k}} \log \ell_{ih_k} \leq \log \ell_{d,\mathrm{critical}}$); i.e., to find the combination of bearers with the minimum number of elements still satisfying the constraint on the overall loss probability.

It is worth noting at this point that the choices available for UE i at the instant t when a decision has to be taken, in order to keep the loss probability below the threshold in a situation of potential danger, may be limited for two reasons: a) the constraint (6) on the maximum number of bearers a gNB j can simultaneously support; b) the choices (if any) made earlier (at times $\tau \leq t$) by other UEs of gNB interfaces inside $\mathcal{A}(i)$. Specifically, indicating by n_j^b the number of such interfaces, for each gNB $j, j = 1, \dots m$, we denote by $\bar{n}_{j,\text{available}}^b = \bar{n}_j^b - n_j^b$ the number of radio bearers that can be instantiated towards gNB j at any step of the construction procedure.

Table 1 – Algorithm – Adaptive reliability through dynamic bearer instantiation

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Set: critical threshold $r$, acceptable loss probability in critical conditions $\ell_{d,critical}$; maximum numbers $\overline{N}_i^b$ and $\overline{n}_j^b$, $i = 1,\cdots, q$, and $j = 1,\cdots, m$, respectively; set $\mathcal{A}(i)$ of all the combinations of bearers that satisfy independence for UE $i$, $i = 1,\cdots, q$.

If at time $t$ the event $d_i(t) \le r$ occurs for a subset $\mathcal{S}_t \subseteq \{1, \dots, q\}$ of UEs, select randomly UE $i$ from the set $\mathcal{S}_t$.

For each UE in $\mathcal{S}_t$, starting from $i$,
  1)
      • remove from the set $\mathcal{A}(i)$ the gNB interfaces which are not currently available;
      • until the number of instantiated radio bearers is ≤ $\overline{N}_i^b$
          – choose, according to pre-specified criteria, one of the combinations which satisfy the constraint (8) with the minimum possible $|N_i^{b,k}|$;
          – decrease $\bar{n}_{j,\text{available}}^b$ by 1 for the involved gNBs $j$;
          – if $\bar{n}_{j,\text{available}}^b = 0$, remove all the combinations involving $j$ from the possible choices for $\mathcal{A}(i)$.
      • if no feasible solution is found (in the worst case, the following has to be repeated for all the UEs in $\mathcal{S}_t$)
          – select randomly UE $\hat{\imath}$ from the set $\mathcal{S}_t \backslash \{i\}$;
          – set $i \leftarrow \hat{\imath}$; $\mathcal{S}_t \leftarrow \mathcal{S}_t \backslash \{\hat{\imath}\}$;
          – for each UE in the set $\mathcal{S}_t$, starting from $i$, repeat the sub-steps of step 1)
          – if still no feasible solution is found, perform appropriate default actions.
  2) whenever $d_i(t) > r$ and $N_i^{b,k} > 1$, keep only the radio bearer associated to the lowest loss probability and de-instantiate the other ones.
End For
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The overall assignment procedure is outlined in Table 1. Note that, in general, the sets $\mathcal{A}(i)$ involved change with time; however, we drop the time index, so as to simplify the notation. It is also worth noting that the choice of UE i at each time t in which the procedure is executed has an impact on the optimization outcome; from an overall perspective, the motivation for making such a choice random is that of providing all the UEs with the "same" opportunity of selecting the feasible combinations associated to the minimum possible number of radio bearers. Finally, we point out that, in case problem (7) with constraint (8) has no feasible solution, some default actions should be undertaken; examples could be to make the robots slow down or stop, or to instantiate a predefined number of redundant radio bearers for all the involved UEs.

4. EVALUATION OF SIMULATION RESULTS

This section shows how the suggested framework may increase network reliability through the above-described adaptation strategy. For this purpose, we have created a Python-coded software simulator to evaluate the performance in terms of the total estimated packet loss probability attained under critical operating conditions, as well as the number of bearers that must be activated for the concerned UEs.

In the context of our simulator, multiple gNBs are deployed to provide indoor mobile radio access to UEs in the whole working area, which is ideally divided into small-squared subareas, each associated with a possibly different value of packet loss probability.

This results in a generally different "coverage map" for each gNB j, $j = 1,\cdots ,m$. Note that, within the simulator, such maps are computed independently for any different gNB, each map including the Block Error Rate (BLER) values resulting from an indoor coverage simulation in the considered industrial environment. As an example, Fig. 2 represents the packet loss rate distribution in the area when only a given gNB is active. The overall packet loss rate perceived by a UE in a certain subarea is then given by the combination of the loss rates of the individual bearers associated to the UE, according to Eq. (8). We point out that the values of BLER are strongly dependent on the payload size, i.e., the amount of data a UE is transmitting to a gNB. We consider a worst-case scenario, in which no error correction/detection code is used; therefore, a single wrong bit in the data block (i.e., the packet) will cause the whole block to be discarded. For this reason, large BLER values can occur even for rather "small" payload sizes (i.e., hundreds of bytes).

The simulator computes trajectories of humans and robots, each one equipped with a UE, with time advancing in discrete steps. For every time unit t the simulator computes the distance $d(t)$ between each pair of UEs, and compares it with the critical threshold r. If some UEs are within critical distance, the simulator tries to compute a suitable bearer allocation such that the requirement on loss rate is fulfilled for each UE. To do that, the simulator solves the optimization problem (7) under constraint (8), currently via exhaustive search, but more efficient search techniques can be (and have actually been [21]) devised. In accordance with the value of packet loss rate mentioned in Section 2, we set $\ell_{d,\text{critical}} = 10^{-6}$. At present, we consider the independence assumption to be satisfied if no UE i is associated to multiple bearers towards a single gNB j.

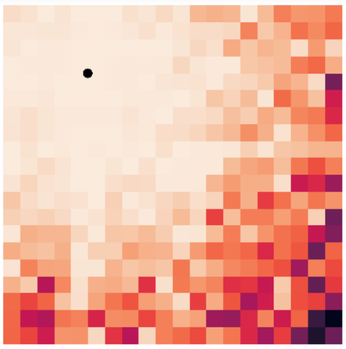


Fig. 2 – Representation of the coverage per subarea provided by a single gNB placed in the top-left quarter of the scenario (black dot), with lighter and darker colours representing lower and higher values of BLER, respectively. Each considered gNB is associated to an individual coverage map, which depends on its location in the work area.

In a first performance evaluation, we consider a large room of width 100 m, length 100 m, and height 10 m, where nine gNBs are deployed, providing access to two UEs, representing a robot and a human, moving according to predefined independent trajectories. The evolution of the distance between the UEs is shown in Fig. 3, where also two different critical thresholds are represented.

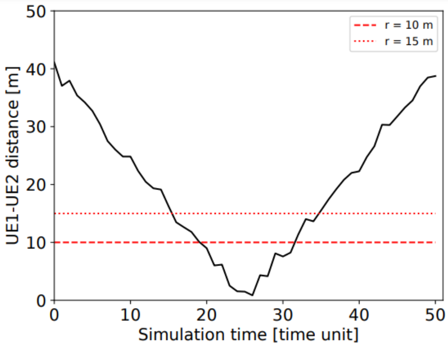
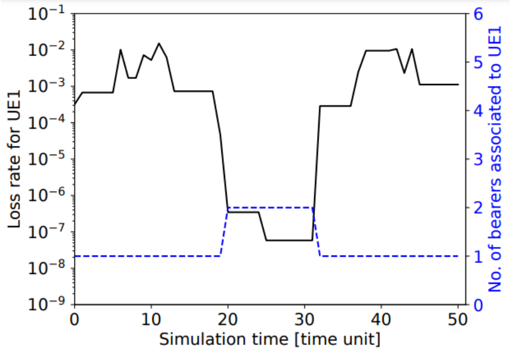
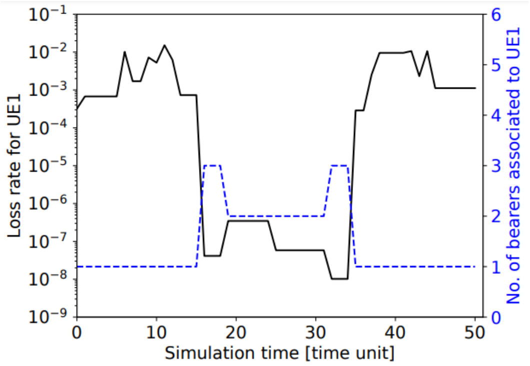


Fig. 3 – Evolution over time of the distance between the UEs considered in the first performance evaluation, with critical thresholds indicated by red lines.



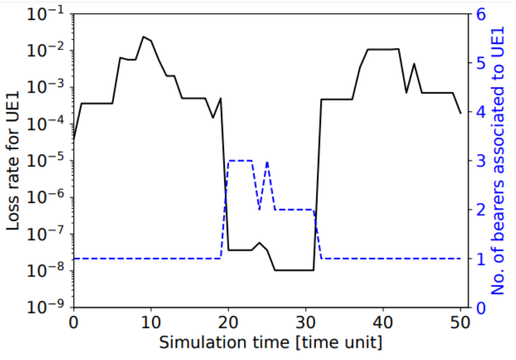
(a) r = 10 m



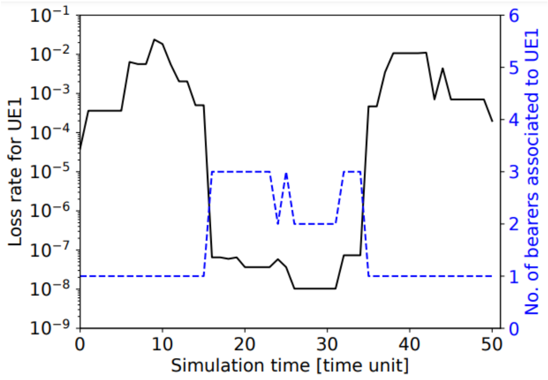
(b) r = 15 m

Fig. 4 – Effects of the adaptive reliability mechanism, under payload = 75 B and two different critical distance values, in the first performance evaluation. The left vertical axis shows the loss rate perceived by UE1 during the simulation, while the right one shows the number of bearers associated to UE1 at every simulation time.

Fig. 4 depicts the loss rate affecting a given UE (solid black line), as well as the number of bearers it needs to instantiate (dashed blue line), under a payload value fixed at 75 bytes (B). Fig. 4(a) and Fig. 4(b) consider different critical distance values. The bearer allocation strategy enables redundant instantiations in correspondence with the time intervals over which the perceived loss rate decreases below the desired threshold. Such redundancy is enforced only when the distance between the two UEs is below the critical one. It is worth noting that the current limitation of a maximum of two bearers per UE allowed by the 5G system would be sufficient for most of the time. However, Fig. 4(b) shows that sometimes three bearers would be needed to fulfil the loss rate requirement. This limitation is even more evident when a larger payload size (resulting in a larger BLER) is considered. Fig. 5 shows the simulation results obtained with the same trajectories as in the previous case, under a payload of 100 B. Owing to the higher BLER, a maximum of four concurrent bearers are required in critical situations. Then, in these scenarios, a 5G system would not be able to satisfy the loss rate requirement for the whole simulated time, highlighting that improvements are needed to comply with such stringent constraints.



(a) *r* = 10 m



(b) *r* = 15 m

Fig. 5 – Effects of the adaptive reliability mechanism, under payload = 100 B and two different critical distance values, in the first performance evaluation. The left vertical axis shows the loss rate perceived by UE1 during the simulation, while the right one shows the number of bearers associated to UE1 at every simulation time.

Fig. 6 shows the average number of bearers necessary for each UE to satisfy the reliability requirement, under different values of critical distance and different payload sizes, for the same UE trajectories as before. The higher the critical distance, the longer the period in which the allocation strategy actively enforces the reliability requirements, thus increasing the overall consumption of radio resources. Conversely, if the critical distance is set to a lower value, the average number of required bearers gets closer to one, meaning that for most of the simulation time a single bearer may be used, without the need of the redundancy mechanism. This means that the critical distance could be seen as a parameter that can be tuned to achieve a trade-off between resource consumption and system reliability. We point out that this parameter also depends on physical characteristics of the involved actors (e.g., robot speeds, robot and human densities, etc.). Finally, the red lines in Fig. 6 indicate that for higher payload sizes the maximum number of bearers per UE grows, as the loss rate values towards each gNB increase.

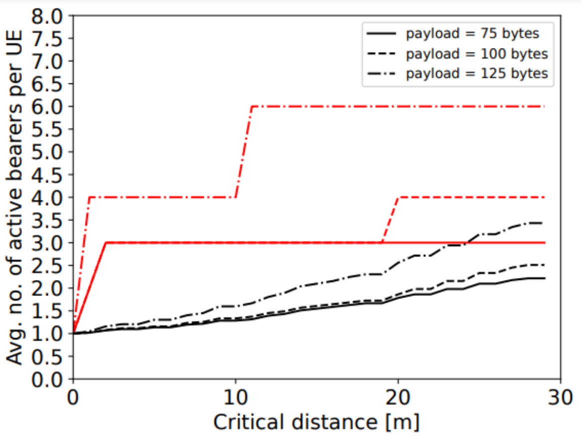


Fig. 6 – Average (black lines) and maximum (red lines) number of bearers per UE over a range of critical distances, under different values of data payload size, when 2 UEs are moving in the area.

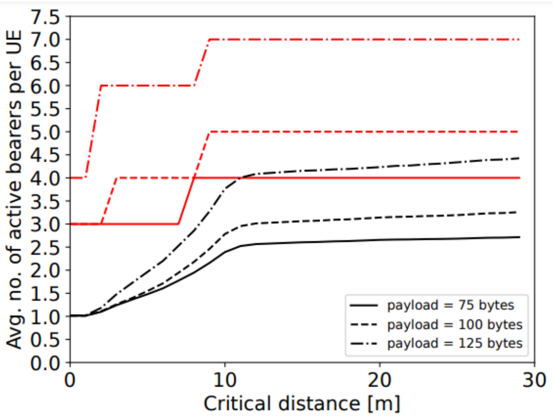


Fig. 7 – Same as Fig. 6, but with 6 UEs moving in the area, 3 humans and 3 robots.

In addition to these simpler results that confirm the ones already reported in [16], we repeated the same simulations, but considering more than two UEs moving in the area over predefined trajectories. Specifically, Fig. 7 refers to the case when six UEs, three of them representing humans and the other three representing robots, are moving in the area along predefined trajectories. We can observe that the need for a higher number of bearers per UE increases rapidly with the threshold on critical distance, i.e., the higher the critical area around UEs, the larger the number of bearers needed per UE to satisfy the reliability requirement. In this scenario, some UEs require up to seven bearers to meet the mentioned requirement. This is expected to worsen for a higher number of UEs in the area, as confirmed by Fig. 8, where the total number of UEs in the area is ten, with the same human-robot proportions as for the previous case (five humans and five robots). In this case, the curves grow faster, owing to the higher density of UEs in the scenario. The maximum number of bearers per UE is unaffected, but this is expected to change by changing the proportion between humans and robots. In Fig. 9 there are still ten UEs moving in the area, but only two of them are carried around by humans, the other eight being carried around by robots. In this case, sometimes up to eight bearers are needed to meet the reliability requirement, and even that is not always sufficient, as there are instances (red dots in the figure) when not all UEs can be assigned a bearer set that meets the reliability requirement. These failures happened owing to the fact that the maximum number of independent bearers that could be associated to a single UE in the simulated scenario was nine (the same as the number of gNBs), owing to the assumption on bearers' independence, and this amount was still not sufficient. This is useful to further prove the point that the higher the number of UEs, the higher the average number of bearers that are needed to meet the reliability requirement.

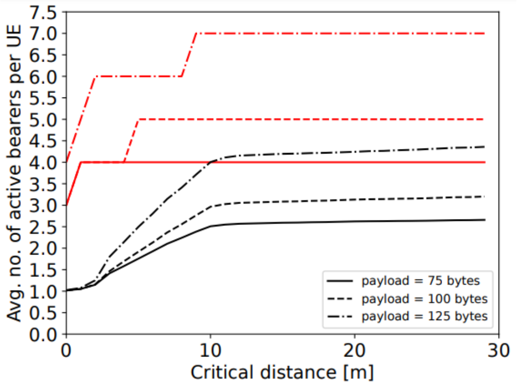


Fig. 8 – Same as Fig. 6, but with 10 UEs moving in the area, 5 humans and 5 robots.

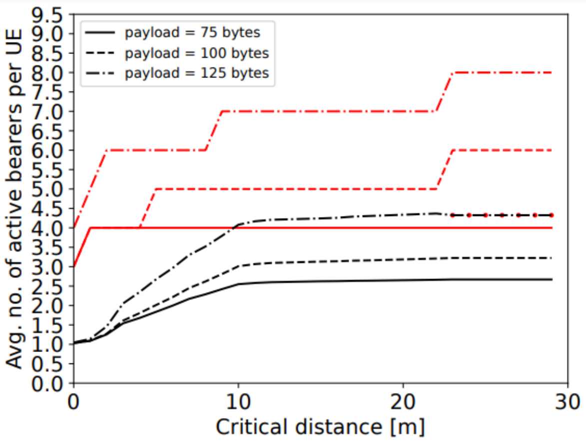


Fig. 9 – Same as Fig. 6, but with 10 UEs moving in the area, 2 humans and 8 robots.

Fig. 10 and Fig. 11 show the probability distribution of a UE to need a certain number of bearers, for different numbers of active UEs in the area, with a fixed value of the critical distance of 10 meters and payload of 100 bytes.

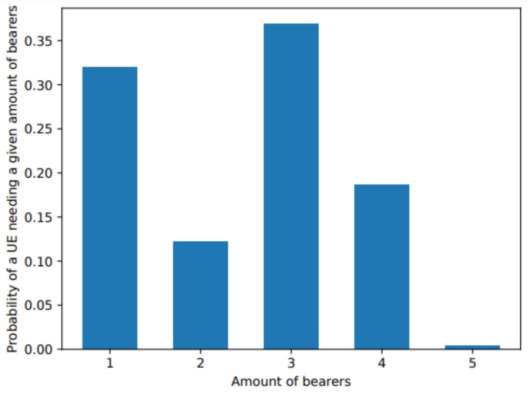


Fig. 10 – Probability distribution of a UE needing a given amount of bearers in order to meet the reliability requirement, when 5 UEs (3 humans and 2 robots) are moving in the area.

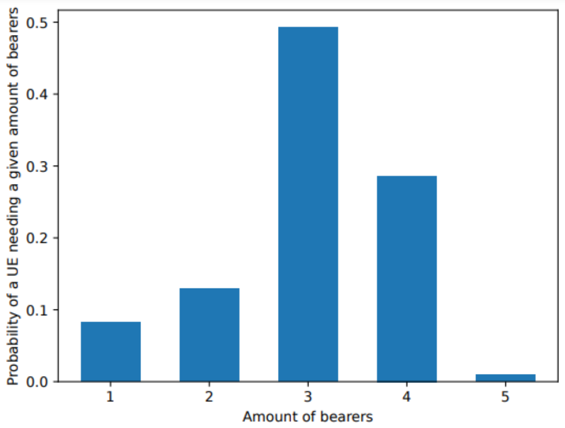


Fig. 11 – Same as Fig. 10, but with 10 UEs (5 humans and 5 robots) moving in the area.

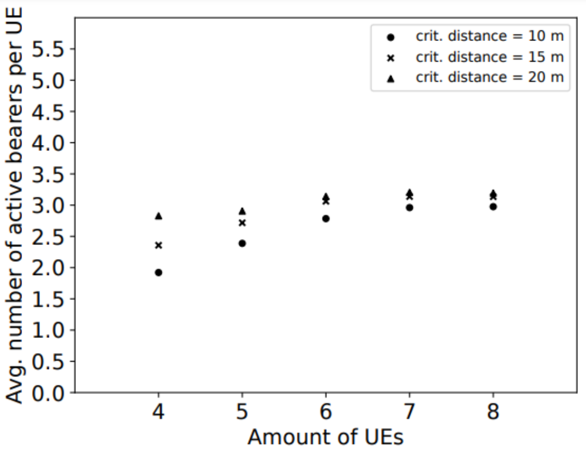


Fig. 12 – Average number of active bearers per UE as a function of the amount of UEs in the area.

Fig. 12 shows the average number of bearers required by each UE as a function of the amount of UEs in the area, with a fixed value of payload of 100 bytes. The fact that the dots get closer as the number of UEs increases shows that the impact of the critical distance threshold decreases for higher densities of UEs in the area.

5. CONCLUSIONS

We have considered in this paper a model to control adaptive reliability for a smart industrial environment where humans and robots are moving. First, we have stated the general formulation of the system in terms of a multi-assignment problem; then, we have considered a refinement of a simple heuristic [16], to find a suboptimal assignment with lesser complexity. Results obtained through simulation (under meaningful simplifying hypotheses) have shown the effectiveness of the proposed approach to provide dynamic reliability requirements and have emphasized the need for a higher number of bearers than the one supported by current 5G specifications, i.e., two. In the conditions considered in the simulations, the number of required bearers can grow up to eight, when ten actors are operating in the scene.

Resource allocation mechanisms such as the one considered in our study allow us to enforce reliability requirements only when needed, thus reducing the overall radio resource consumption. Future work could concern an analysis of the required data acquisition mechanisms and of the execution times of the algorithm, along with the impact of handover time on control plane latency. Additional simulations should be carried out including a larger number of UEs in the scenario. Ultimately, the heuristic adopted should also be compared with alternative approaches to solve the general multi-assignment problem, such as appropriate auction algorithms.

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