( one6G )

Taking communications to the next level

# 6G & ROBOTICS

## Identifying Use Cases and Potential Service Requirements - Methodology and Examples

WHITE PAPER

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# Scope

The one6G Association recognizes the growing demand for robotic applications in various fields such as logistics, automation, healthcare assistance, and delivery. The integration of wireless sensing, communication, and computation capabilities in robotic systems can enhance reliability, capability, and operational efficiency while reducing complexity and cost. In the future, it is envisioned that 6G communication systems will empower robotic applications. Concurrently, the mobile communication industry is working to understand the system requirements of robotic applications to inform the design and architecture of the future 6G communication system. A detailed analysis of these requirements is necessary to identify technical problems and challenges specific to robotic applications. By accurately identifying these problems, appropriate technical solutions can be developed from a communication system perspective.

In a previous white paper [1], the one6G Association proposed multiple use cases for robotics and highlighted the potential role of the upcoming 6G communication system. Various use cases in healthcare assistance, industry-related scenarios, remote operation, automation, and inventory management were described and discussed. In the white paper, use cases were classified based on the type of interaction between robots, humans, and controllers, which helped recognize the potential of the 6G communication system in enabling these use cases.

In a follow-up investigation, a second white paper [2] presented a methodology for determining the requirements of 6G robotic use cases across different dimensions such as wireless sensing, communication, computation, and the support of artificial intelligence or machine learning (AI/ML). The methodology represents use cases as a combination of phases, atomic functions, and use case specific atomic function handlers. Depending on the use case, the atomic functions interact in different ways and have specific requirements in the aforementioned dimensions. The methodology provides examples based on the use case classifications from the previous white paper to demonstrate how to establish system requirements. Baseline system requirements have been derived for different categories, including wireless sensing, communication, and AI/ML, for each atomic function and handler per use case class. By having detailed system requirements for each atomic function, the future 6G system can be optimized to provide network services for robotic use cases in a cost-effective and sustainable manner.

In this whitepaper, a selection of robotic use cases are discussed, detailing requirements for communication services and sensing operations to support robotic operations within two important scenarios: robot-to-robot cooperation and disaster recovery operations. A variety of use cases are presented which consider the functional requirements for supporting multimodal sensing operations (e.g. 3D mapping, object detection & identification, environment modelling), aspects related to robot autonomy and AI, aspects related to robot control and actuation, and many more topics of interest for 6G robotics applications. The two scenarios explored in this white paper are intended to be the first step towards further consideration of robotics use cases and requirements. Additional use cases will be considered in future volumes of the one6G 6G and Robotics series of white papers.

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# 1. Definitions of terms

In this section, we present a set of definitions for terms related to robot capabilities, use cases (UCs), as well as different functionalities and KPIs. The KPIs are defined in terms of system requirements for robotic applications, including perception and sensing capabilities, connectivity requirements, and AI/ML support.

## 1.1. System level definitions

Robot-to-Robot interaction (R2R): when multiple robots cooperate with each other to achieve a common task. Robot-to-robot interaction enables a group of robots to reach consensus on how to execute a common task. The shared information may include motion plans, perception information, as well as cooperative control actions. The communication direction in the communication system that enables robot-to-robot interaction is sidelink [1] [2].

Atomic Function: refers to an independent and compact function implemented in an entity (e.g., robot or network) that interacts with other independent functions over defined interfaces. The atomic function concept allows the decomposition of each UC phase into smaller components performed by UC actors (e.g. robots). Multiple atomic functions may be associated to a phase. An atomic function may be common to multiple UCs [2].

Atomic Function Handler: is a type of atomic function that is specific to a UC and therefore it is specialized to a certain type of UC. An atomic function handler triggers the execution of other atomic functions specific to a UC. Different handlers are associated to different types of actions performed by robot, e.g. perception or actions (defined below) [2].

Robotic UC class: is a template of atomic functions and handlers common to all robotic UCs that belong to a specific class. There is a one-to-one mapping of each robotic UC interaction type group to each robotic UC class.

System Requirements: refer to the required performance level in terms of wireless communication and sensing, AI/ML support and robotic capabilities that future 6G communication system must fulfil to enable robotic UCs.

## 1.2. Robotic UC capabilities

Here, some relevant information from one6G 6G & Robotics whitepaper vol. 1 [1] is summarized for reference.

Perception: refers to the key capability of the robot to perceive and comprehend about unstructured (real) environments in which they operate and act. Perception is required in many applications, and is typically enabled by sensory data and AI/ML techniques. Examples of perception capability include object detection, scene understanding, human/pedestrian detection, activity recognition, and object modelling, among others.

Reasoning and decision making: refers to a robot's ability to reason, learn, and make decisions based on its perception of the environment, which involves higher-level cognitive processes such as planning, decision-making, and problem-solving to perform complex tasks autonomously [3].

Actuation & Control: refers to a robot's ability to act on its environment based on its perception and cognition, which involves the manipulation of physical objects and the execution of motor commands to move the robot's body.

## 1.3. 6G Robotic UCs

Motion Plan: is the sequence of valid spatial configurations that a robot executes to perform motion from a source to destination location. It may be computed locally by a robot or computed externally by the network or other robots [4].

Pre-grasp: the phase of robot motion that occurs before grasping of an object. For example, moving the base of the robot in to a suitable position, and configuring the robot arms to be close to the grasping point. No dynamic interaction with the object to be grasped occurs in the pre-grasp phase.

Levels of Autonomy: these describe a robot's ability to deal with its environment on its own, and work for extended periods of time without human intervention [5].

- Automated robot: A role for a robot performing a given task in which the robot acts as an automaton, not adapting to changes in the environment and/or following scripted plans [6]. For instance, the motion planning is defined by operator and each machine actuator change is specified by the operator, e.g. for haptic or tele-operation.
- Semi-autonomous robot: A role for a robot performing a given task in which the robot and a human operator plan and conduct the task, requiring various levels of human interaction.
  - Partial control: Operator partially controls a robot. For instance, the operator specifies general movements or position changes and the robot decides the specific movements of its actuators.
  - Supervisory/Task-level autonomy: The operator specifies only the high-level task and the robot manages the motion planning & control routines needed to enable task completion.
- Fully autonomous robot: A role for a robot performing a given task in which the robot solves the task without human intervention while adapting to operational and environmental conditions. Therefore, perception, reasoning and decision are all performed by the robot(s).

Different autonomy levels may also imply the dependency of the robotic system on the communication system. Moreover, the autonomy level depends on usage scenarios and industry sectors. For instance, cars on public streets will execute most of the perception and cognitive control using local sensors and computing resources. In campus networks like factories, the perception and cognitive control are performed in a more centralized manner. AMR (autonomous mobile robots) are typically provided with a list of waypoints from a central fleet management system and also a regular update of the environment map in order to compute the detailed movement trajectories on a local controller.

Service Availability: is the percentage value of the amount of time the end-to-end communication service is delivered according to a specified quality of service, divided by the amount of time the system is expected to deliver the end-to-end service [4].

Transfer interval: is the time difference between two consecutive transfers of application data from an application via service interface to network [4].

## 1.4. Communication terms and KPIs

**Communication Direction:** refers to who transmits to whom over a wireless channel, i.e., from network to robot (downlink), from robot to network (uplink) and robot to robot (sidelink).

**Communication Mode:** refers to the number of involved transmitters and receivers in the wireless communication. Unicast corresponds to one-to-one communication, groupcast corresponds to one-to-many communication, fusion refers to many-to-one and broadcast corresponds to one-to-all communication.

**Communication Availability:** refers to the ability of the communication service to perform as required for a given time interval, under given conditions [4].

**Communication Data Rate:** refers to the amount of data bits transmitted over a wireless channel during a defined time window [Bits/s] [4].

**Communication Reliability:** refers to the proportion of transmitted bits that are correctly decoded by receiver within a given time period (%) [4].

**Communication Latency:** refers to the amount of time it takes to transfer a packet from source transmitter to destination receiver, measured at the communication interface [msec] [4].

**Communication Jitter:** refers to the variation of communication latency from consecutive packets that have arrived at the receiver [msec].

## 1.5. Wireless sensing terms and KPIs

**Wireless Sensing:** is the capability of the 6G communication system to get accurate information about objects within environment (e.g., shape, size, velocity, orientation, location or distances or relative motion between objects) using wireless signals (either reusing communication signals or using dedicated sensing signals) [7].

**Accuracy of Positioning Estimate:** describes closeness of measured sensing result (i.e. position) of target object to its true position value [m] [7].

**Accuracy of Velocity Estimate:** describes the closeness of the measured sensing result of the target object's velocity to its true velocity [m/s] [7].

**Refresh Rate:** is the inverse of the time elapsed between two successive sensing results [1/s] [7].

**Sensing Resolution:** describes the minimum difference in measured magnitude of target objects (e.g., range, velocity) to be allowed to detect objects in different magnitude [7].

## 1.6. AI/ML support KPIs

**Max allowed downlink end-to-end latency (Model Transfer):** in the context of AI/ML model distribution, is the maximum time a robot may wait to receive an AI/ML model transfer from network [8].

**Max allowed downlink end-to-end latency (AI/ML split inference):** in the context of AI/ML split inference, is the maximum time a robot may wait to receive an AI/ML intermediate result from network [8]. Split inference refers to when AI/ML model (e.g., a neural network model) is split among multiple entities during inference.

**Max allowed uplink end-to-end latency (AI/ML split inference):** in the context of AI/ML split inference, is the maximum time a network application (e.g., implemented in an edge server) may wait to receive an AI/ML intermediate result from robot [8].

# 2. Overview

This white paper addresses the existing and expected roles of wireless communications and sensing in supporting the operation of robots in vertical industries. The expected key enablers are the integration of communication and wireless sensing, as well as high data rate, high service availability and low-latency wireless access to data processing functions and AI/ML services.

The scope for application of robotic technology is vast, encompassing many industries including logistics, industrial automation, service robotics, healthcare, and more. As a strategy to narrow the search space for robotics use cases, we first consider robotics use cases belonging to distinct 'scenarios', i.e. certain applications of robotics technologies that are likely to present a connected set of requirements and KPIs. For a given scenario, a number of key factors can differentiate the importance of certain KPIs for supporting robotic operations. These factors include:

- Environment (i.e. indoor or outdoor, structured or unstructured, etc)
- Object(s) for interaction (size, shape, weight, regularity, fragility)
- Autonomy level (tele-operated, semi-autonomous, supervised autonomy, full autonomy, etc)

In this white paper, we focus on two particular scenarios: Robot-to-Robot (R2R) interaction cases, where multiple robots collaborate to achieve a common task, and Remote or damaged environment (RDE) cases, where due to e.g. limited communication coverage communication-aware motion planning and control for robots becomes crucial. It should be noted that, although many of the use cases in the RDE scenario are presented in the example of disaster recovery robotics, these use cases are intended to be generalised as part of further one6G white papers.

In the subsequent subsections, the R2R and RDE scenarios for robotics use cases are discussed in general. Robotics use cases defined within these scenarios are presented in Section 3; additional use cases are presented in Annex B for further development.

## 2.1. Scenarios for robotics use cases

### 2.1.1. Robot-to-Robot

Cooperative carrying refers to a set of mobile robots cooperating with each other to transfer objects such as metal frames or parcels, from one place to another, for example, in factories. Depending on the object characteristics, and number of mobile robots, the level of cooperation may vary. The level of cooperation indicates the requirements in terms of coordination between the mobile robots. For example, a rigid, fragile and heavy object requires more precise coordination among the mobile robots compared to a soft elastic object. Additionally, the robots may be capable of carrying several different kinds of objects with varying characteristics. These object types/characteristics needs to be appropriately identified in order to determine the level of cooperation and enable the execution.

The characteristic features of this scenario are as follows:

- Environment: indoor (factory), outdoor (delivery), combined scenario of ground mobility and aerial mobility; (e.g., agriculture), combined scenario of over ground and underground mobility (e.g., mining); irregular and/or unstructured setting.

- **Object(s):** weight, size, shape, color, and material:
  *Other parameters included:*
  - Size (e.g. 2 or more robotics required for group carrying)
  - Material characteristics (e.g. fragile, solid, or soft), which may affect haptics or force characteristics
  - Robots' lower sensitivity to haptic/force may add stringent latency requirements below 1ms
- **Autonomy levels:** e.g. human-in-the-loop, network-assisted, and full autonomy:
  *Other parameters included:*
  - Controller design method
  - Deployment options: controller in the cloud, edge, or device
  - Characteristic of robots with respect to sensing (e.g., haptic, vision), movement (rolling on wheels or drones), size, energy, intelligence, and capabilities (e.g. degrees of freedom)
  - Trajectory: pre-defined (mostly for indoor), arbitrary (mostly outdoor)

### 2.1.2. Remote or damaged environment

A key application area for networked mobile robots is in disaster recovery. For many years, the robotics community has sought to design mobile robots which are well suited for assisting in search and rescue efforts in extremely challenging conditions [9]. As an example, the Fukushima power plant disaster of 2011 was the inspiration for academic research and government challenges, e.g. the DARPA Robotics challenge [10], to pursue robotic approaches to future disaster recovery situations. The general aim of disaster robotics is to provide a safe robotic solution for assisting with health and rescue efforts, especially in circumstances where it is too dangerous or inefficient for human rescuers [11] [12].

Typically, we can expect the disaster robots utilized in these scenarios to comprise a heterogeneous cluster of mobile robots with manipulation capabilities (e.g. quadrupeds, mobile manipulators, humanoids) and highly mobile robots for diagnostics and sensing (e.g. UAVs). Note that some but not all robots in the team require manipulation capabilities, and that mobility can in this case come from legged locomotion.

In disaster areas, local communications infrastructure is likely to be impacted – **however, a core assumption of all use cases in this scenario is that at least some network infrastructure (e.g. base stations) remains operational**. Teams of robots require communication capabilities for effective collaboration, either for sharing data or computational resources with other members of the robot team, or for communicating with a remote server to receive control commands or data processing functionality. In addition, in cases where disaster areas are too unsafe for human workers, it is important in many cases to be able to create and maintain wireless communication to transfer audio-visual and diagnostic data to human operators. As such, flexible wireless communication technologies and approaches such as long-range and sidelink R2R communication are vital to the application of robots in disaster zones.

The characteristic features of this scenario are as follows:

- **Environment:** outdoor, unstructured, dynamic, poor visibility due to air particulates (smoke, dust) and limited lighting

- Object(s): heavy objects, unstructured shapes, human-robot interaction possible, remote link to human operators: remote inspection and diagnostics (common), remote control or audio-visual transfer (as needed, high reliability)
- Autonomy level: expected to be teleoperated, semi-autonomous; fully autonomy possible as robotics & AI technology continues to advance

## 2.2. Use case template

The use cases presented in this white paper follow a common format intended to align to the expectations of SDO's. Here, this format is presented, with a brief description for each subsection.

### 2.2.1. Description

General description of the background and intention of the use case.

### 2.2.2. Pre-conditions

Any pre-conditions which need to exist for this use case, i.e. from functionalities which are already present in the 3GPP network.

### 2.2.3. Service flows

A sequence of simple steps outlining the events that comprise a use case. Each step should clearly indicate the information flow and the agents involved (e.g. "sensing data from 3rd party to network").

### 2.2.4. Post-conditions

The end result of the use case, highlighting the benefit of the additional functionality.

### 2.2.5. Existing features partly or fully covering the use case functionality

Existing features in the specifications that support this use case.

### 2.2.6. Potential new requirements needed to support the use case

Features that are not present in the specifications, but are required in order for the use case to be carried out successfully.

## 2.3. Functional requirements/KPIs and Atomic Functions & Handlers

Fundamental perception, cognition, decision and reasoning, or control & actuation sub-tasks performed by robots (discussed in Whitepaper vol 1 [1]) are common in different robotic UCs. In Whitepaper vol 2 [2], we defined fundamental robotic subtasks as 'atomic functions'.

These are compact and independent functions that interact with other independent functions over defined interfaces.

To consider the functional and quantitative requirements of 6G robots, as a first step it is useful to consider the core functions underlying robot motions and actions, i.e. the atomic functions and atomic function handlers introduced in previous one6G white papers. As a specific example, further details of a cooperative carrying UC are described in UC Cooperative Carrying with Robots in 6G & Robotics one6G white paper [1], and the three robotic UC phases and the atomic functions and handlers that support the goal of each phase and the interactions between the phases in the subsequent white paper [2].

An atomic function is mapped to a fundamental robotic capability, namely: perception, cognition, and control, as outlined in 6G & Robotics one6G white paper [1]. Therefore, an atomic function can be translated to functional requirements for these capabilities. For example, an atomic function handling perception can infer requirements on one or more of 3D mapping capabilities, positioning accuracy, sensing adaptation, and environment modelling accuracy, depending on the use case.

Further consideration of the relationship between atomic functions and handlers and robotics use cases is presented in tabular form in Annex B.

# 3. Robotics use cases

## 3.1. Use case on assessing infrastructure damage in cities

### 3.1.1. Description

When a city is affected by a natural disaster, such as an earthquake, it is important to quickly assess the damage done to infrastructure (roads, buildings, power stations, etc). This information is needed to direct search and rescue (SAR) efforts – for example, so that emergency responders can be directed to areas which have significant damage to residential or office buildings. Without this information, delays in SAR response to areas that have sustained high damage may result in a loss of human life. Assessment of infrastructure damage through cameras and other sensors may be impeded by low visibility due to air particulates, damage (e.g. destroyed camera hardware), or limited internet connectivity after the disaster. Instead, damage to infrastructure can be assessed efficiently by comparing data from 3GPP and non-3GPP sensing sources, pre- and post- disaster.

### 3.1.2. Pre-conditions

As part of disaster response preparations in a city, the local government has an agreement with mobile operator X to support disaster response activities. As part of this service, a snapshot of 3GPP and non-3GPP sensing data of the city infrastructure is stored on a regular basis, e.g. once a month. Mobile operator X owns and manages base stations throughout the city. In addition, some UE's with non-3GPP sensors (e.g. robot sensors) are registered to operator X and distributed throughout the city.

### 3.1.3. Service flows

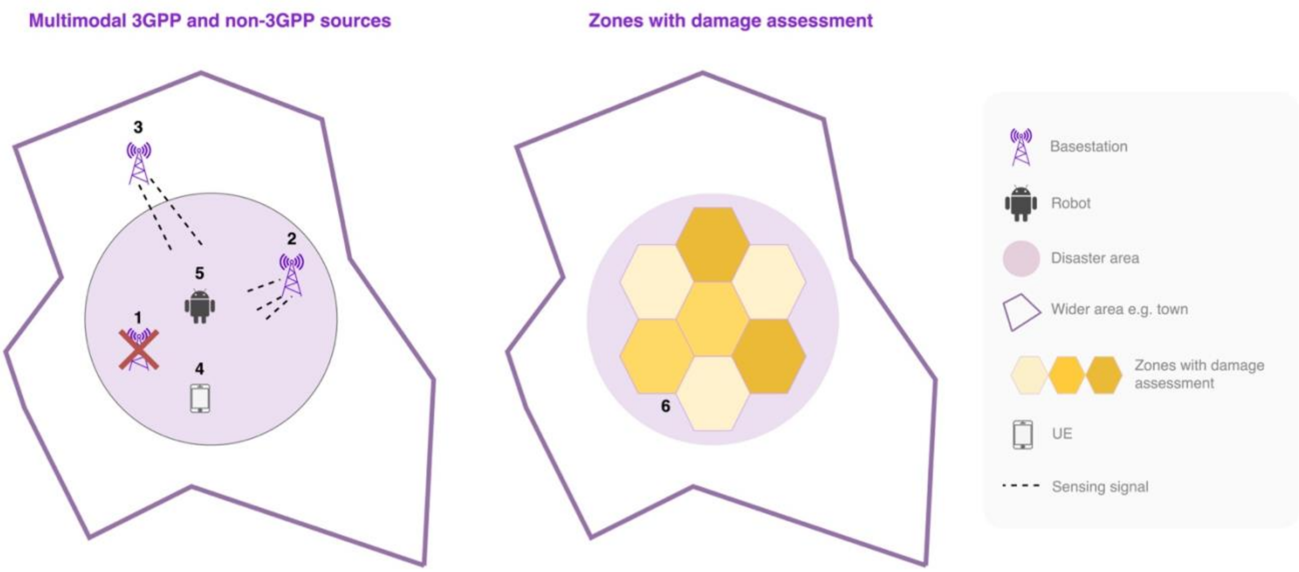


*Figure 1: Assessing infrastructure damage after natural disasters*

- Step 1. An Earthquake hits the city, causing widespread power cuts, low visibility, and damage to infrastructure in the area. A SAR team is assigned to respond to the disaster. The SAR team requests mobile operator X to provide an assessment of infrastructure damage in the city.
- Step 2. Mobile operator X carries out radio-based sensing of the infrastructure throughout the city. Radio waves are transmitted by operational base stations (2, 3) owned by operator X throughout the city. These radio waves reflect off of buildings, roads, and other infrastructure, before returning to the transmitting base station, resulting in an RF (radio frequency) point cloud.
- Step 3. Mobile operator X requests UE's registered in the city with sensing capabilities (4, 5) to transmit sensing signals, both RF (i.e. monostatic sensing) and non-RF (e.g. from a robot with mounted UE). Similar to step 2, this results in a series of RF and non-RF point clouds for each UE. This provides more detail in areas with non-operational base stations (1).
- Step 4. The RF and non-RF point clouds are combined to generate a single point cloud for the city, e.g. via multimodal sensor fusion.
- Step 4. The pre-disaster and post-disaster point clouds are compared to assess the extent of damage based on the differential in point cloud information.
- Step 5. The resulting information is returned to the SAR crew as zones with damage assessment (6).

### 3.1.4. Post-conditions

Infrastructure damage is successfully assessed. With this assessment, SAR crews can optimise their actions to reach areas of high urgency more quickly. This can potentially save human lives.

### 3.1.5. Existing features partly or fully covering the use case functionality

[EF 3.1.5-1] Provide disaster or emergency sensing results to authorized third parties [7].

[EF 3.1.5-2] Non-3GPP sensing data can be collected and combined with 3GPP sensing data [7].

### 3.1.6. Potential new requirements needed to support the use case

[PR 3.1.6-1] Subject to regulation and operator's policy, the 3GPP network shall be able to collect, process, store and regularly update 3GPP and non-3GPP sensing data for mission critical services.

[PR 3.1.6-2] Subject to user consent, regulation, and operator's policy, the 3GPP network should be able to combine 3GPP and/or non-3GPP sensing data, including real-time and data stored for e.g. mission critical services, based on geographical location and time stamps, for a sensing result based on the request from a trusted third-party.

## 3.2. Use case on sensing for environment mapping in disaster areas

### 3.2.1. Description

Navigating in disaster environments is difficult for robots due to the damage to roads and presence of rubble and other obstacles. Typically, robots utilise a 'map' (see Definition 3.2.1 below) of their environment for motion planning. After a natural disaster, any stored map of an environment can be expected to be out of date, and on-the-fly mapping by robots is likely to be inefficient e.g. due to dead ends. Instead, the network can generate a map from 3GPP sensor data.

Definition 3.2.1 – Environment Map

A representation of the environment (typically a 2D or 3D grid of cells) which stores the location of obstacles, goals, free space, etc. Numerical values associated with each cell can be used in robotic motion planning to promote using or avoiding certain cells.

### 3.2.2. Pre-conditions

Operational gNB's and UE's in a disaster area have the capability to perform 3GPP sensing.

### 3.2.3. Service flows

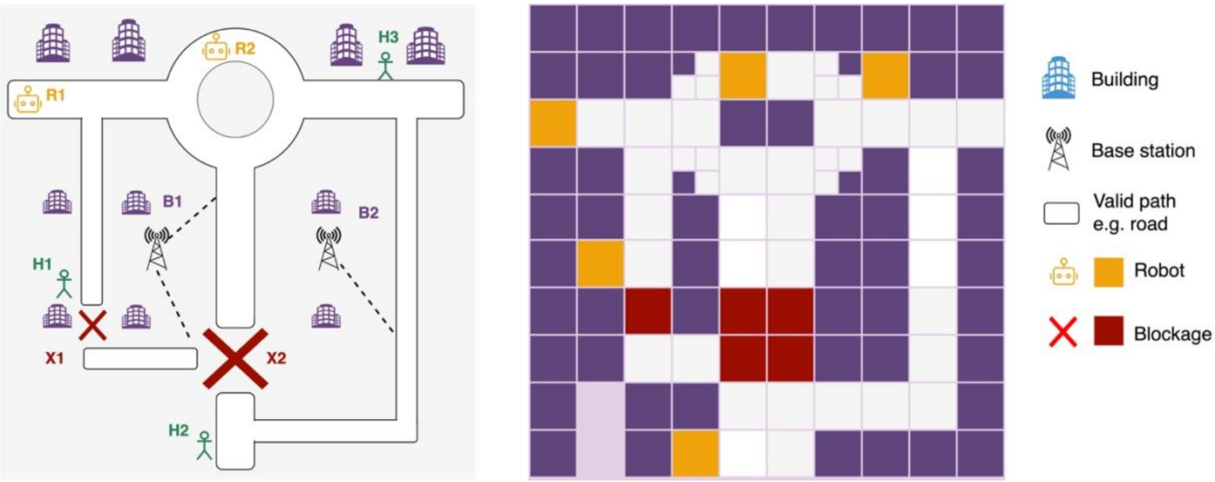


*Figure 2: generating environment maps for robot motion planning*

- **Step 1.** A SAR service requests Mobile Operator X for a sensing service to update a map of the environment since their existing environment map is no longer usable.
- **Step 2.** The SAR service uploads the existing map to the network. Alternatively, this map could be maintained internally by Mobile Operator X via a cooperation agreement (e.g. as in Use Case 3.1).
- **Step 3.** Mobile operator X carries out radio-based sensing throughout the mapped region using operational base stations (B1, B2), UE's mounted on robots (R1, R2), or non-3GPP sensing (e.g. robot sensors). Monostatic sensing is carried out at operational base stations.

- Step 4. The collected 3GPP and non-3GPP sensing data is combined by the network for further processing, considering prior environmental information e.g. the existing map.
- Step 5. The network provides sensing results to identify road blockages and potential entities within the map, based on the sensing service request and mobile robot capability provided by the SAR service. For example, referring to the map as a grid of cells shown in Figure 2, presence of objects in cells of the grid corresponding to roads can be identified as a blockage (X1 & X2; red); meanwhile, objects of humanoid shape can be classified as entities (orange).
- Step 6. The sensing results, including e.g. map location, are returned to the trusted 3rd party, i.e. the SAR service, by the network.

### 3.2.4. Post-conditions

With the sensing results from the network, an updated map is created for SAR services, which allows for efficient motion planning of mobile robots within the area e.g. to target accessible routes.

### 3.2.5. Existing features partly or fully covering the use case functionality

[EF 3.2.5-1] Provide disaster or emergency sensing results to authorized third parties [7].

[EF 3.2.5-2] Authorized third parties can configure 3GPP system to initiate sensing for disasters [7].

### 3.2.6. Potential new requirements needed to support the use case

[PR 3.2.6-1] The network shall have the capability to receive environment maps uploaded from trusted 3rd parties e.g. government search and rescue services, for the purpose of conducting targeted sensing services.

[PR 3.2.6-2] The network shall have the capability to perform targeted sensing based on existing environment maps, e.g. to detect the presence of blockages on previously accessible routes.

[PR 3.2.6-3] Subject to regulation and operators' policy, the 6G system shall provide secure means for a trusted third-party to receive sensing results of classifying characteristics of the environment and/or objects at specific locations, e.g. access condition, location of entities, etc.

[P4 3.2.6-4] The network shall be able to provide the sensing service with the following KPIs:

*Table 1: Performance requirements for environment mapping in disaster situations*

| Scenario | Sensing service area | Confidence level [%] | Accuracy of positioning estimate by sensing (for a target confidence level) | | Accuracy of velocity estimate by sensing (for a target confidence level) | |
|---|---|---|---|---|---|---|
| | | | Horizontal [m] | Vertical [m] | Horizontal [m/s] | Vertical [m/s] |
| Environment mapping in disaster situations | Outdoor | 99 | ≤1 | ≤1 | N/A | N/A |
| | Sensing resolution | | Max sensing service latency [ms] | Refreshing rate [s] | Missed detection [%] | False alarm [%] |
| | Range resolution [m] | Velocity resolution (horizontal/ vertical) [m/s x m/s] | | | | |
| | N/A | N/A | <10000 | < 10 | < 1 | < 1 |

## 3.3. Use case on sensing for identification of casualties in disaster situations

### 3.3.1. Description

In disaster situations, the main goal of the initial search and rescue response is to locate human casualties, i.e. humans who may be injured and require urgent assistance, and differentiate them from other entities. However, due to damage to infrastructure and poor visibility, this task is challenging. Wireless sensing can be used to generate environment maps (Use Case 3.2) but it can be difficult to differentiate between entities of similar size e.g. humans and robots. By providing the functionality for material classification via enhanced wireless sensing, the network can provide a service to differentiate between objects, humans, and robots in disaster situations.

### 3.3.2. Pre-conditions

Operational gNB's and UE's in a disaster area have the capability to perform wireless sensing and material classification.

### 3.3.3. Service flows

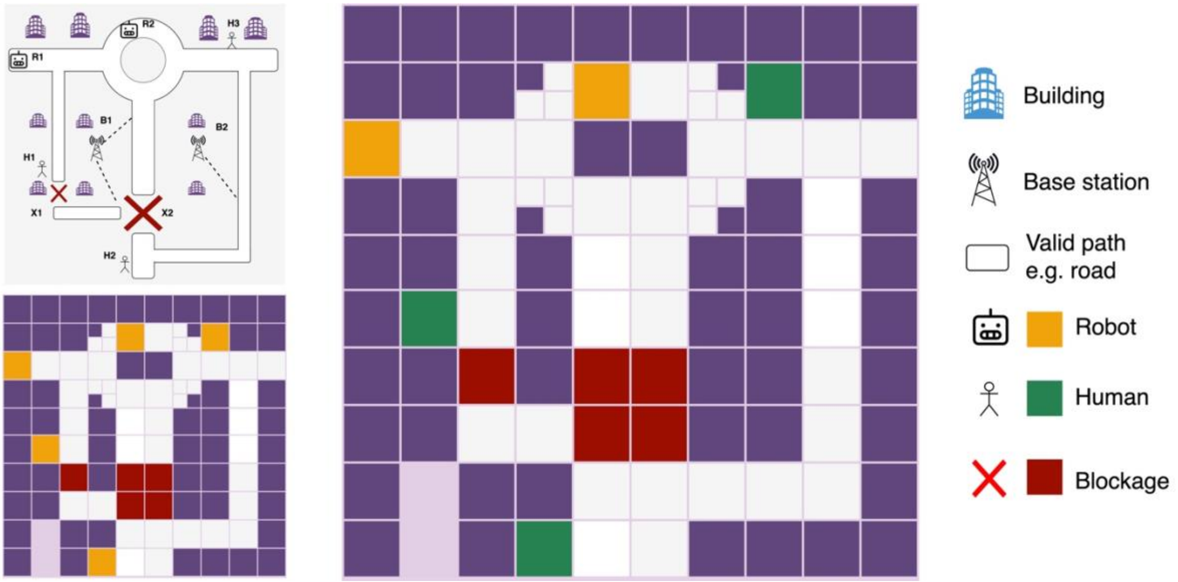


*Figure 3: Identification of casualties in disaster situations*

- Step 1. A SAR crew requests Mobile Operator X for a sensing service to identify human casualties at in a city following a disaster situation.
- Step 2. The SAR crew specifies possible sensing locations (SL's). Alternatively, these locations could come from a map obtained from the SAR crew or from a network service (e.g. Use Case 3.2 on sensing for environment mapping).
- Step 3. Mobile operator X carries out radio-based sensing at the SL's using operational base stations (B1, B2) or UE's. Monostatic sensing is carried out at operational base stations.
- Step 4. If applicable, UE's (e.g. embedded on robots connected to the network) collect high resolution multimodal (3GPP and non-3GPP) data, i.e. those robots which are in range of a specific SL.
- Step 5. The resulting sensing measurements are transferred from the RAN to the network for processing.
- Step 6. From the processed sensing data the object(s) detected at the sensing locations are characterised, e.g. according to size, shape, detection of movement, material characterization, etc.
- Step 7. The likelihood of humans being present at each SL is calculated. For example, referring to the map as a grid of cells shown in Figure 3:
  - Large, irregularly shaped, static objects are unlikely to be humans and may be classified as rubble or other obstacles (X1 & X2; red)
  - Objects which are mobile but with non-biological material characteristics may be classified as robots (R1, R2)
  - Sensing measurements which are mobile and correspond to biological material characteristics (H1) may be classified as a human in motion
  - Sensing measurements which are static and correspond to biological material characteristics (H2) may be classified as a static human (potentially a target for rapid assistance)

- **Step 8.** The processed results from the sensing service, i.e. likelihood of humans present at the SL's along with auxiliary information, is returned to the 3rd party, i.e. the SAR service, by the network. If the SL's were derived from a map in S2 the resulting information can be embedded directly in to the map for use by the 3rd party.

## 3.3.4. Post-conditions

Key targets (blockages, robots, humans) operating in the space are differentiated via material classification. With this differentiation, SAR crews can optimise their actions to reach human casualties more quickly. This can potentially save human lives.

## 3.3.5. Existing features partly or fully covering the use case functionality

[EF 3.3.5-1] Provide disaster or emergency sensing results to authorized third parties [7].

[EF 3.3.5-2] Authorized third parties can configure 3GPP system to initiate sensing for disasters [7].

## 3.3.6. Potential new requirements needed to support the use case

[PR 3.3.6-1] The network shall have the capability to classify materials based on sensing results, i.e. to determine whether a humanoid shaped figure is human or robotic based on the sensing data. In particular, the material characterisation should allow distinguishing between biological and non-biological materials.

[P4 3.3.6-2] The network shall be able to provide the sensing service with the following KPIs. Note that the horizontal velocity measurement is based on a minimum observed walking speed of 0.23m/s of adults with injuries or otherwise requiring rehabilitation [13].

*Table 2: Performance requirements for identification of casualties in disaster situations*

<table>
<tr><td rowspan="6">Scenario<br>Identification of casualties in disaster situations</td><td rowspan="2" colspan="2">Sensing service area</td><td rowspan="2" colspan="2">Confidence level [%]</td><td colspan="2">Accuracy of positioning estimate by sensing (for a target confidence level)</td><td colspan="2">Accuracy of velocity estimate by sensing (for a target confidence level)</td></tr>
<tr><td>Horizontal [m]</td><td>Vertical [m]</td><td>Horizontal [m/s]</td><td>Vertical [m/s]</td></tr>
<tr><td colspan="2">99.9</td><td colspan="2">≤1</td><td>≤1</td><td>≤0.2</td><td>N/A</td><td>99.9</td></tr>
<tr><td colspan="2">Sensing resolution</td><td rowspan="2">Max sensing service latency [ms]</td><td rowspan="2">Refreshing rate [s]</td><td rowspan="2" colspan="2">Missed detection [%]</td><td rowspan="2" colspan="2">False alarm [%]</td></tr>
<tr><td>Range resolution [m]</td><td>Velocity resolution (horizontal/ vertical) [m/s x m/s]</td></tr>
<tr><td>N/A</td><td>N/A</td><td><10000</td><td>< 1</td><td colspan="2">< 0.1</td><td colspan="2">< 1</td></tr>
</table>

# 3.4. Use case on link scheduling for robotic motion planning

## 3.4.1. Description

Robot instructions are typically high-level: 'go to this point', 'move these objects', 'pick up this item', etc. To actually carry out these instructions, a motion plan is generated which involves a combination of ***motion components*** – e.g. grasping, locomotion, manipulation, etc. These motion components have different requirements from a communications perspective. For greater efficiency when supporting robot motion plans, the requirements for each motion component should be met by the RAN according to the schedule of the overall motion plan. Especially in disaster environments where communication bandwidth as a whole is limited, it is important to supply high speed and/or low latency communication links when needed but to conserve resources when not.

## 3.4.2. Pre-conditions

Operator X supplies a service to support robotic motion planning operations. Robot motion plans can be decomposed in to motion components by a network service.

## 3.4.3. Service flows

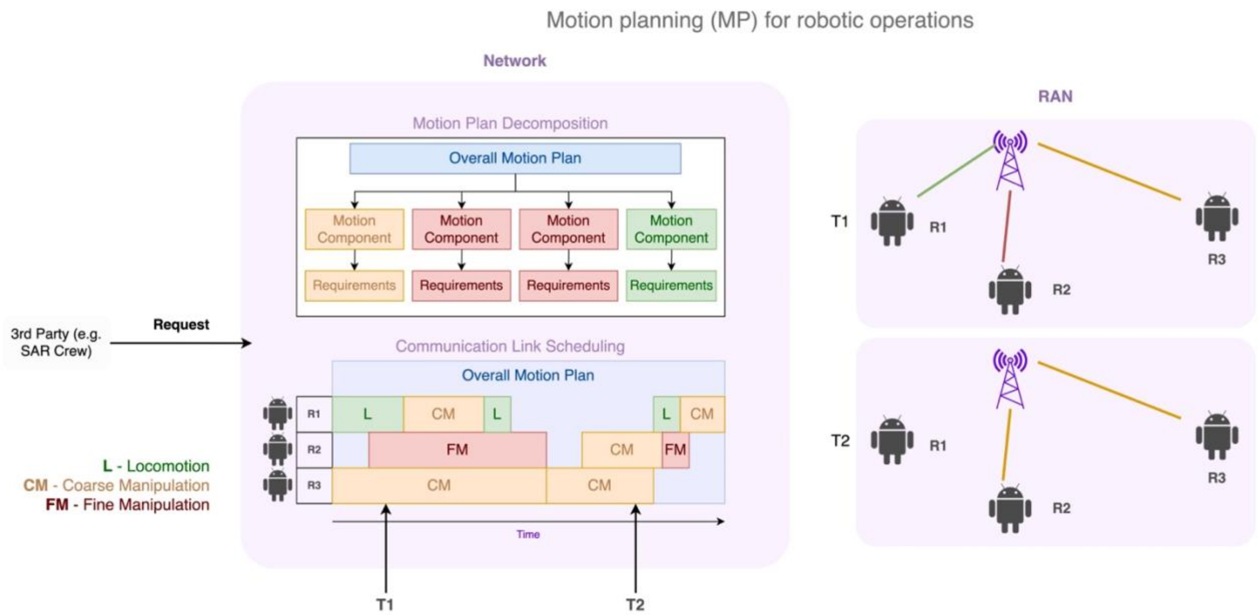


*Figure 4: Link scheduling for robot motion planning*

- Step 1. SAR crew requests Operator X to support with a robotic motion plan. In this plan, a mobile robot (R1) approaches a humanoid robot (R2), which takes an object from R2, then passes the item to a third humanoid robot (R3).
- Step 2. The network decomposes the motion plan in to motion components and associates the appropriate communication requirements to each component given the network configuration (i.e. capability of UE's on R1 – R3 and capabilities of local base stations).

- Step 3. Communication link schedule is generated based on the schedule of motion components in the input robot motion plan.
- Step 4. Communication links are established according to the schedule, e.g. at time T1 we have R1, R2 and R3 connected with normal, low latency and ultra-low latency links, respectively. At time T2 robot R1 requires no link while robots R2 and R3 require low latency links only.

### 3.4.4. Post-conditions

The robot motion plan is carried out and each robot receives the appropriate communication link for each component of the motion plan. This saves resources and ensures that robots have adequate communication links for each stage of the task.

### 3.4.5. Existing features partly or fully covering the use case functionality

None.

### 3.4.6. Potential new requirements needed to support the use case

[PR 3.4.6-1] Based on operator policy, the 3GPP network shall internally store the communication requirements of components of robotic motion, e.g. grasping, fine grasping, 2D locomotion, 3D locomotion, etc.

[PR 3.4.6-2] Based on operator policy, the network shall support scheduling communication link(s) to robots by decomposing robotic motion plans in to motion components and subsequently selecting the appropriate schedule of communication links according to the stored communication link requirements.

## 3.5. Use case on communication-aware motion planning

### 3.5.1. Description

Maintaining connectivity during robotic operations is vital both for networked planning and control but also to ensure communication links to human rescue crews are uninterrupted. This is challenging in disaster scenarios due to the typically limited or damaged infrastructure, as well as the likelihood for historical QoS data to be inaccurate. The same is true in areas with fully functional but limited wireless connectivity, e.g. remote locations or on offshore sites, which may have limited or incomplete historical QoS data. Therefore, robot motion planning must take network conditions in to account. This can be achieved via communication-aware motion planning.

### 3.5.2. Pre-conditions

Robots are registered to the 3GPP network and have an embedded UE for communications.

### 3.5.3. Service flow

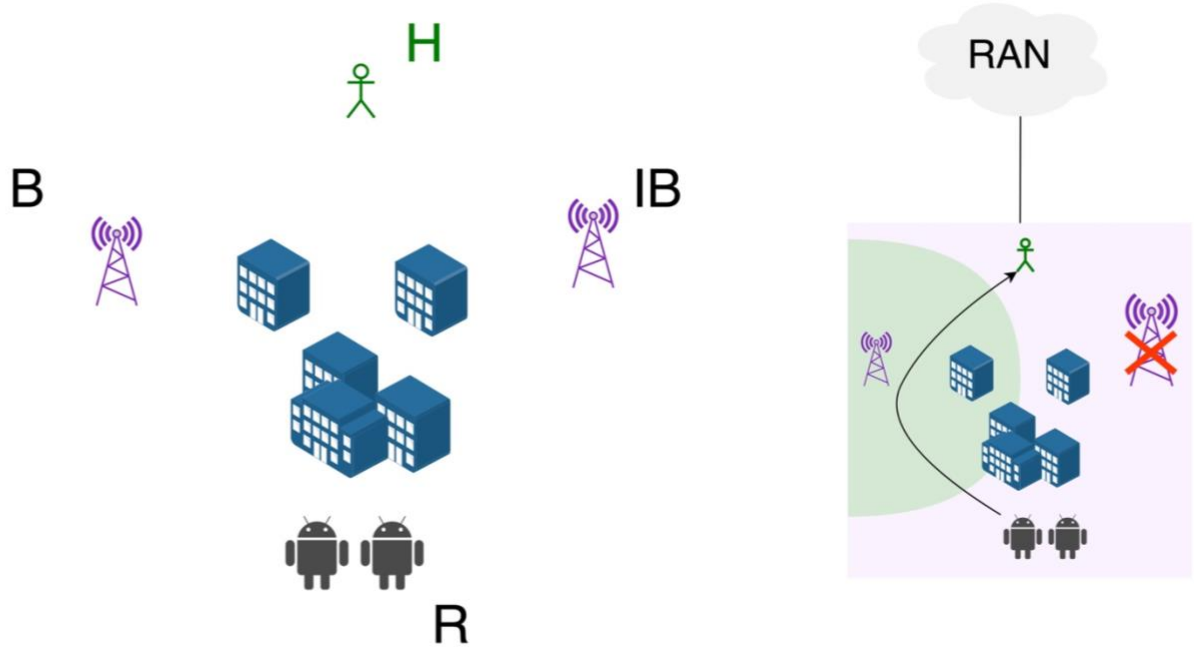


*Figure 5: Communication-aware motion planning*

- Step 1. SAR crew requests Operator X to handle robotic operations in a communications-limited area. A group of robots (R) is tasked with navigating to a human target (H), navigating around buildings. There are multiple possible routes.
- Step 2. In this case, the historical quality of service data does not provide a good estimate of link quality, since one of the nearby base stations is in-operational (IB). Instead, the predicted link quality of the network in the area encompassing the navigation task is computed, for example via computational techniques e.g. using ray tracing on an environment map with material characteristics (Use Case 3.1 – 3.3) from wireless sensing.
- Step 3. The area with high predicted link quality (green region surrounding the operational base station, OB) is computed and returned to the 3rd party, e.g. as coordinates with associated predicted link quality.
- Step 4. The SAR crew directs the robot along a path which maintains high link quality.
- Step 5. During the robot operations, the environment map is maintained by continuous 3GPP and non-3GPP sensing, e.g. from the base station as well as the UE's on the robot and the robot's sensors. Updates to the predicted link quality are transmitted to the 3rd party during operations, allowing for adaptations to the initial motion plan.
- Step 6. The group of robots (R) successfully reaches the target and the service is terminated.

### 3.5.4. Post-conditions

Robots carry out motion plans which ensure connectivity is maintained, resulting in e.g. better networked control, and stronger communication links between robots and the network.

### 3.5.5. Existing features partly or fully covering the use case functionality

[EF 3.5.5-1] Network can provide predicted quality of service (PQoS) e.g. using historical QoS data.

### 3.5.6. Potential new requirements needed to support the use case

[PR 3.5.6-1] Based on operator policy, the 3GPP network shall support requests to provide sensing services for communication-aware motion planning from trusted 3rd parties e.g. during robotic operations in remote areas.

[PR 3.5.6-2] Based on operator policy, the 3GPP network shall support the provision of predicted quality of service/link quality information for a requested area based on 3GPP and non-3GPP sensing data.

[PR 3.5.6-3] Based on operator policy, the 3GPP network shall support the continuous update of predicted link quality information based on real-time updates of sensing information, e.g. from wireless sensing at base stations and/or UE's, and from non-3GPP sensing sources.

## 3.6. Use case on physical interaction between cooperative robots

### 3.6.1. Description

Physical interaction between robots requires a combination of sensing (of objects and the environment) and communications (between robots, e.g. R2R communication). For example, robots, which are cooperatively relocating heavy rubble (i.e. target objects) from a disaster site, need to exchange sensing measurement data among themselves and base stations, in order to retrieve information of that rubble including material/localization/shape/orientation, select/approach grasping points of the rubble for robot grasping, and subsequently carry out the grasping and lifting of the rubble.

### 3.6.2. Pre-conditions

- Two or more robots are cooperating to clear a rubble blocking entry to a building.
- The robot behaviour is orchestrated by a task planner (TP), which can be provided by a 3rd party e.g. one of the robots or an external device.
- Each robot has an on-board motion planner (MP) and local controller (LC). The LC's operate with a refreshing rate of 1ms.
- Each robot has an embedded UE with ISAC capability.
- Each entity (robot, base station, TP) is connected to the 6GS, which manages the sensing task.
- No humans are present in the vicinity during the task.

### 3.6.3. Service flows

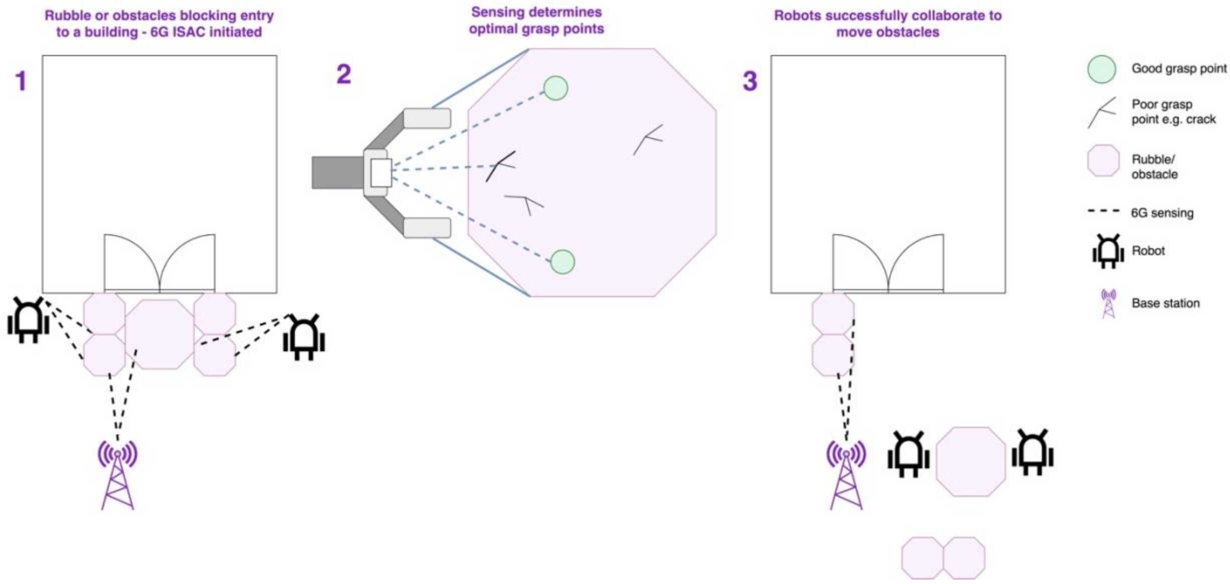


*Figure 6: Physical interaction between cooperative robots*

1. The TP requests the 6GS for high resolution sensing of the rubble to aid in the grasping of rubble while clearing it from the entryway (Figure 6, Step 1).
2. The 6GS coordinates the sensing task for the UE's and the base station.
   - Local UE's with high resolution, short-range sensing capabilities sensing capabilities collect high resolution data from the surface of the rubble close to robots.
   - The base station collects data at lower resolution but wider range of the scene, e.g. of the whole collection of rubble blocking the entryway.
   - The resulting sensing data is fused and returned to the TP.
3. The TP determines the optimal grasping positions (Figure 6, Step 2), and transfers these positions to the MP on each robot.
4. The robot MP's plan and execute the pre-grasp phase for each robot.
5. On completion of the pre-grasp phase, the TP requests a low latency, high reliability link to be established between the robots. The 6GS establishes such a connection between the UE's mounted on each robot.
6. The TP initiates the remaining stages of the motion.
7. The robot MP's plan and execute the remaining stages for each robot.
8. The LC's on each robot use their local sensing data and the fast refresh rate (1ms) interaction data (force, haptics) transmitted from the partner robots to maintain stability of the motion during execution.
9. Once the object is deposited in a new location (Figure 6, Step 3), the TP requests the 6GS to close the low latency link in preparation for further sensing and to save resources.
10. The TP transfers the next locations for each robot to the robot MP's (i.e. to bring them back in to range of the rubble for sensing). The MP's plan and execute this motion.
11. Steps 2 – 10 are repeated until the TP specifies the task as complete.

### 3.6.4. Post-conditions

The robots successfully clear the area of rubble. With ISAC from robot UE's and nearby base station(s), grasp positions were determined efficiently. Low latency communication links allowed for reactive collaboration.

### 3.6.5. Existing features partly or fully covering the use case functionality

[EF 3.6.5-1] High reliability transfer of haptic data (99.9999999%) is already supported for extended reality applications with humans as the end user [14].

### 3.6.6. Potential new requirements needed to support the use case

[PR 3.6.6-1] The high reliability requirement of haptic data for extended reality applications with humans as the end user should be extended to the robot collaboration domain.

[PR 3.6.6-2] An additional sensing mode (short range THz) is supported by UE's for increased sensing KPIs for close ranged operations.

[PR 3.6.6-3] UE's have the ability to switch between sensing modes depending on task, in particular to and from the above short ranged THz mode.

[PR 3.6.6-4] The network shall be able to provide the following KPIs:

- Accuracy of positioning estimates are required of 0.01m (horizontal/vertical) are required for robot manipulation tasks, e.g. detection of grasp points on objects.
- Confidence level of fine-positioning estimates should be 99% if only robots are present in the environment. High confidence is required as the consequences for a failed grasp hold can be significant in terms of damage to robots.
- Transfer of dynamic interaction data between robots requires low latency, e.g. 0.001 – 0.01s [15], and high reliability. This is an enhancement compared to existing 3GPP requirements on factory and public safety [7].

## 3.7. Use case on sensing for post-earthquake damage assessment and survival detection

### 3.7.1. Description

The deployment of first responders to disaster-affected areas is largely carried out by law enforcement and national authorities within the framework of current communication capabilities. However, telecommunication infrastructure can be damaged due to high-intensity natural disasters, resulting in increased time and cost of traditional ground route-based SAR missions. The use of alternative communication links e.g. un-crewed aerial vehicles (UAVs), narrowband Internet of Things (NB-IoT) based communication, and non-terrestrial networks, promises to improve the effective utilization of SAR resources (personnel, equipment, medical aids, etc.) in such situations and, therefore, minimize the loss of causalities.

### 3.7.2. Pre-conditions

The SAR crew has the authority to use the 3GPP NB-IoT service of a mobile base station that has been deployed to the disaster area.

The UAV can carry a 3GPP-compliant NB-IoT BS for a certain time period. The BS has the capability to perform array processing for direction of arrival estimation purposes. The buildings for which damage assessment is required are equipped with NB-IoT devices, either inside or outside the buildings.

Each NB-IoT device contains a set of sensors with different modality (e.g., RF sensor, a thermal sensor, a voice recognition module), and has sufficient computational power to perform the required signal processing (e.g., RF-based motion detection, body temperature detection, and human voice detection) by using the data received from these sensors.

The NB-IoT devices have a fully charged battery prior to the disaster, and are configured to operate for a certain period when the energy infrastructure is cut off. NB-IoT devices are capable of starting to use their battery capacity with the help of a wake-up signal transmitted by the BS.

### 3.7.3. Service Flows

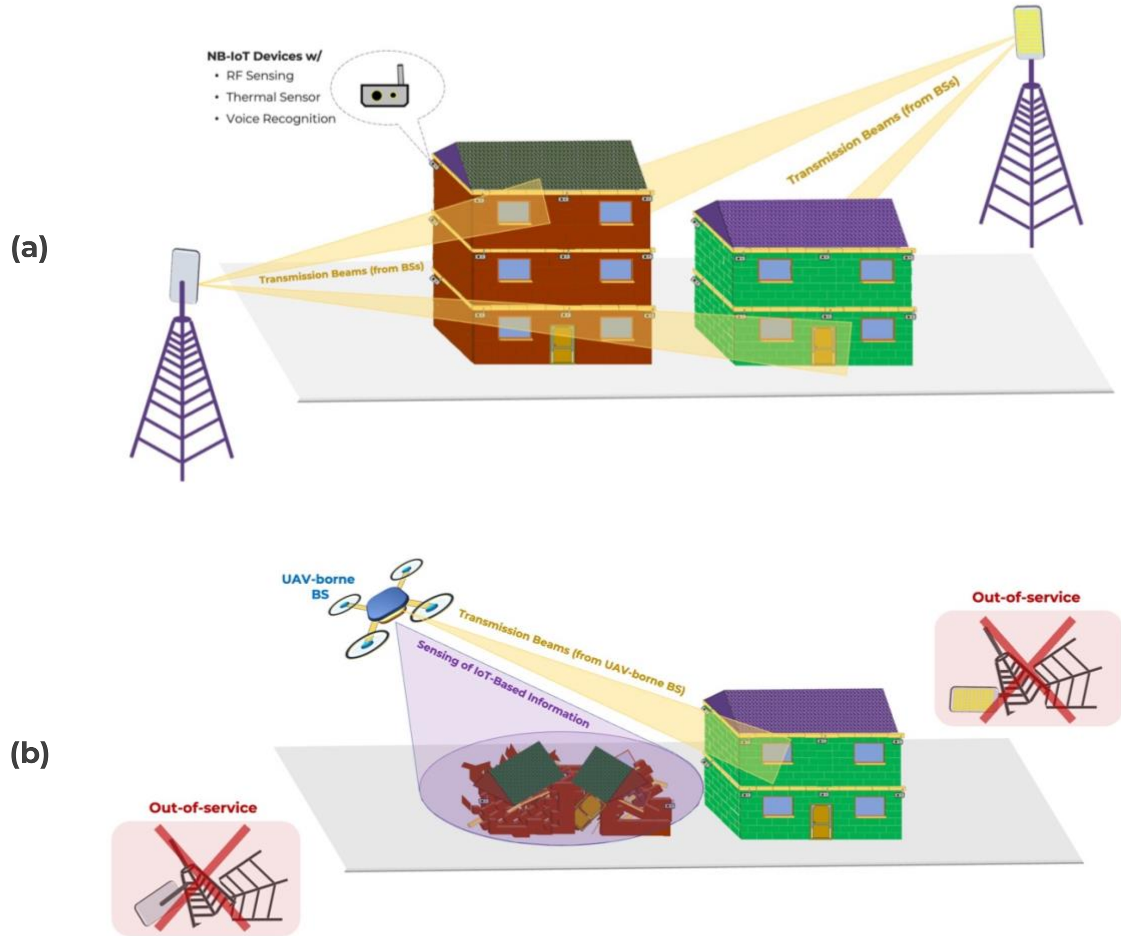


*Figure 7: Representative sketches for (a) an ordinary operation case, (b) a post-disaster operation case.*

- Step 1. During the ordinary operation as illustrated in Figure 7-(a), the telecommunications infrastructure serves user equipment as per their communication requirements, and the NB-IoT devices are operated in sleep (idle) mode.
- Step 2. A building and nearby base station are damaged following a natural disaster. The NB-IoT devices remain under the building debris.
- Step 3. In the initial moments of the post-disaster process, UAV platforms, which are tasked with providing input for SAR missions and are based on NB-IoT or similar principles for damage assessment and survival detection, are managed by a central authority and directed to different disaster sites.
- Step 4. The UAV platform, which has arrived at the disaster area as depicted in Figure 7-(b) and is carrying the NB-IoT BS equipment, broadcasts a wake-up signal in time-division duplex (TDD) mode along a predefined route to operationally trigger the NB-IoT devices.
- Step 5. The NB-IoT devices, which are wirelessly activated, use their internal energy to drive the RF and thermal sensors and the voice recognition module they contain, enabling these components to respectively detect RF-based motion and biometric signals, e.g. heart palpitations, body temperature, and human voice, under the debris.
- Step 6. Subsequently, the NB-IoT devices transmit the processed data focused on detection and recognition processes carried out by the various sensors they contain to the 3GPP-compliant NB-IoT BS during the uplink phase of the TDD time frame.
- Step 7. Upon reception of the processed detection and recognition data, the UAV-mounted BS evaluates the estimated angular information of the IoT devices and scales the severity of the disaster and consequently the amount of damage by calculating the extent to which the devices have been displaced compared to their pre-disaster positions.
- Step 8. By jointly evaluating the processed sensor data, the UAV-mounted BS (or application server) periodically monitors the number of survivors under the debris. Thereafter, crucial information about SAR requirements is communicated to the central management mechanism.

### 3.7.4. Post-conditions

The data collected and processed by UAV-mounted BSs will be evaluated together at a central management station. A damage map for the entire examination area is created and effective utilization of the limited SAR resources is ensured.

### 3.7.5. Existing features partly or fully covering the use case functionality

[EF 3.7.5-1] The wireless communications system shares narrowband data produced by the 3GPP-compliant NB-IoT communication infrastructure, which includes disaster damage assessment information and sensor detection results, with authorized third-party institutions/organizations [7].

### 3.7.6. Potential new requirements needed to support the use case

[PR 3.7.6-1] The 6G network shall support rapid deployment of mobile units (e.g., UAVs carrying NB-IoT base stations) and non-terrestrial networks (e.g., HAPS, satellites) to ensure continuous connectivity and data transmission capabilities immediately following a disaster.

[PR 3.7.6-2] The 6G network shall support fusion of real-time 3GPP and non-3GPP sensing data to provide a comprehensive assessment of the environment, e.g. via AI/ML support for real-time data processing. This includes data from RF sensors, thermal sensors, and voice recognition modules to detect motion, body temperature, and human voices under debris. The sensor fusion service shall run on the network or on the application-level via a trusted 3rd party.

[PR 3.7.6-3] Authorization and Data Privacy: The use of 3GPP and non-3GPP sensing data must comply with regulatory and operator policies, ensuring data privacy and user consent where applicable. This includes secure transmission and storage of data, as well as regulated access by authorized third parties for mission-critical services.

[PR 3.7.6-4] Devices should be configured to operate efficiently on battery power with capabilities to perform motion detection, temperature monitoring, and voice recognition using minimal energy, e.g. via energy efficient 3GPP sensing. They should also be capable of receiving wireless trigger signals to activate post-disaster.

[PR 3.7.6-5] Subject to regulation and operator's policy, the 6G system shall support classifying characteristics of the environment and/or objects at specific locations, e.g. access condition, type of entity, location of entities, etc.

[PR 3.7.6-6] Further to PR 3.7.6-5, and subject to regulation and operators' policy, the 6G system shall provide secure means for a trusted third-party to receive sensing results of classified environment or object characteristics.

[P4 3.7.6-7] The 6G network shall be able to provide the sensing service with the following KPIs:

*Table 3: Performance requirements for post-earthquake damage assessment and survival detection*

| Scenario | Sensing service area | Confidence level [%] | Accuracy of positioning estimate by sensing (for a target confidence level) | | Accuracy of velocity estimate by sensing (for a target confidence level) | |
|---|---|---|---|---|---|---|
| | | | Horizontal [m] | Vertical [m] | Horizontal [m/s] | Vertical [m/s] |
| **Scenario** post-earthquake damage assessment and survival detection | Outdoor | 99 | ≤1 | ≤1 | ≤0.2 | ≤0.2 |

| Sensing resolution | | Max sensing service latency [ms] | Refreshing rate [s] | Missed detection [%] | False alarm [%] |
|---|---|---|---|---|---|
| Range resolution [m] | Velocity resolution (horizontal/ vertical) [m/s x m/s] | | | | |
| ≤0.25 | N/A | <10000 | < 10 | < 0.1 | < 0.01 |

# 4. Conclusion, recommendations, & next steps

This whitepaper extended the investigations from previous one6G white papers [1] [2] in to 6G Robotics use cases and requirements. A series of use cases were presented across two vertical scenarios in robotics: robot-to-robot cooperation, and robotic operations in remote or damaged environments. For each use case, a number of functional or quantitative requirements were identified which are required to enable the use case, but are not yet supported by the current 3GPP network (5GS). From this analysis of robotics use cases, it is clear that there is great potential for the upcoming 6GS to offer meaningful functionality to improve the operation of robots in these two scenarios.

The recommendations from the analysis in this white paper are two-fold: firstly, the use cases presented in this document should continue to be refined with the aim of submitting UCs to SDOs, such as 3GPP SA1 or ETSI. Secondly, considering the breadth of expected usage of robotics in the industries of the future, it is important to consider additional use cases – both within the scenarios already discussed here, as well in additional scenarios within robotics. Potential scenarios of interest could include: medical robotics, assistive and rehabilitative robots, service robots, robots for package delivery, and many more. One potential area for collaboration between one6G work items is between the 6G Robotics & e-Health work items – i.e. in the intersection between robotics & e-Health. These recommendations should inform the direction of the next instalment (vol. 4) of the one6G 6G & Robotics whitepaper series.

In terms of research & development for 6G technology, by means of conventional resource provisioning (i.e., actuation, communication, computation and sensing resources), the future 6G communication system can meet most demanding requirements. However, technology directions such as the co-design of communication and control may help relax system requirements of the different robotic use cases and therefore meet system requirements in a more sustainable way. In this way, 6G communication system can scale more efficiently and enable an increased uptake of robotic applications in different vertical domains.

In summary, it is recommended that future work can consider and build upon this whitepaper to work towards clear enhancements of communications requirements relevant for the robotic vertical industries of the future.

# Annex A
## Robotics use cases for further consideration

### A.1 Use case on resource distribution for robotic operations

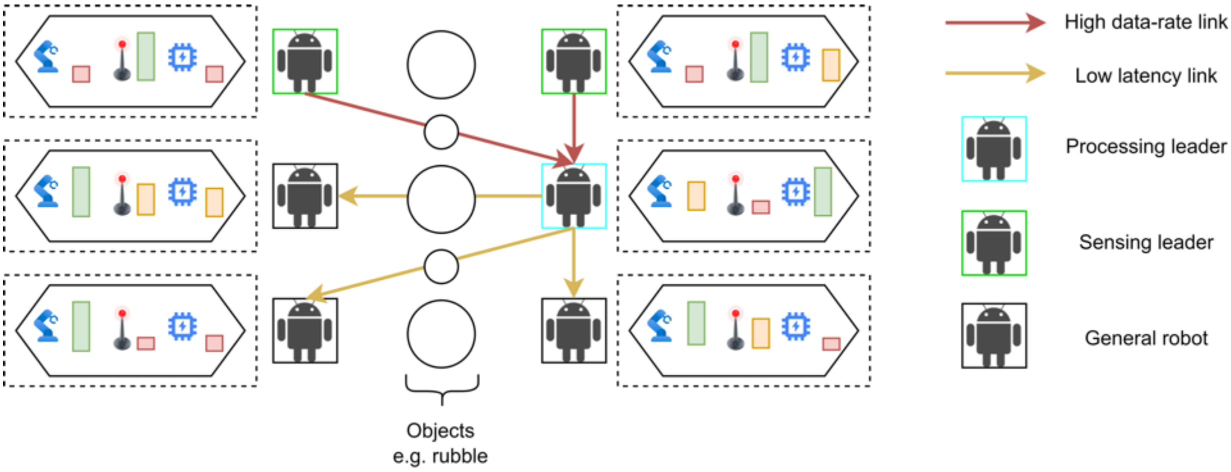


*Figure 7: Resource distribution for robotic operations*

Disaster robots can be expected to vary significantly in computational or sensing capabilities, including 3GPP sensing. Meanwhile, the data transfer & processing requirements of robotics tasks are high. Given the damage to communications infrastructure at disaster sites, uplink and downlink data rates can be expected to be limited, and therefore the mechanisms and KPIs to support robot-to-robot communications be important for robot cooperation tasks.

This use case should explore how the network can distribute communication resources (e.g. bandwidth, latency) to individual robots carrying out a task so as to optimize task performance (e.g. according to application-level KPIs reported by the robots). For example, we can consider a task whereby robots collaborate to move rubble, where robots have mixed sensing and processing capabilities (Figure 7). Possible requirements on the network to carry out this use case could include:

- Robot-specific registration allowing the network to determine the processing and sensing capabilities of robots
- Enhancements to direct robot-to-robot communications KPIs in the case that high data-rates are required. For example, to achieve fast control loops on robots with insufficient processing capabilities, it may be preferable to transfer sensing data via a bi-directional, low latency direct connection to a more powerful robot nearby for computation of control commands

### A.2 Use case on cooperative robot fleets for delivery

In this scenario, autonomous vehicles are envisaged in high population environments where last mile delivery supposes a critical service for urban freight transport. These vehicles equipped with community lockers provide an improvement in terms of delivery time and reduction of air pollution. Another key advantage is the reduction of traffic congestions due to the capacity of these vehicles to move on roads and sidewalks. However, the navigation capabilities for this aim must be considerably improved to move the robots between humans and vehicles autonomously through the enhancement of sensor acquisition by utilizing 6G networks.

Moreover, the management of these vehicles provides another key challenge where fleets must keep transmitting information to a central coordinator and other vehicles. Additionally, remote control must be ensured in case that any robot faces urgent situations.

## A.3 Use case on transport of materials in industry logistics

This use case is focused on scenarios where robot fleets must transport different materials throughout an industry environment, e.g. within warehouses or from an outdoor depot to a warehouse. A global supervisor based on a software executed in a cloud or local server controls the existence of different tasks that are necessary for the correct behaviour of the warehouse. Therefore, this supervisor assigns different tasks to the robots, in order to proceed with correct transport of the materials.

Following this approach, a task can be split into three steps. Firstly, the robot that receives the task must move to the location of the pod where the material is placed. Secondly, the robot moves the pod to a target location where the material will be handled. Finally, once the pod is empty, the robot will transport the pod to a final position for its fulfilment.

With the objective to carry on this scenario, robot fleets must export data from embedded sensors to the global supervisor. Additionally, sensing from radio infrastructure is necessary to provide sensor fusion that enables the best path design from the supervisor to avoid dynamic obstacles. Therefore, the following service requirements are identified:

- Support for real-time AI/ML model downloading and distribution among robots based on their new tasks.
- Integration of communication and control.
- Extremely high uplink data rates for sensor data transmission from the robots.
- New sensing capabilities that provide obstacle detection.
- Fulfilment of sensing KPIs, e.g., sensing resolution, positioning.

# Annex B - Summary of atomic functions and use case requirements

| Atomic function/handlers | Potential Functional requirements to support Use Case | | KPI Value Discussion |
|---|---|---|---|
| | Met in 5GS | Partially met/not met | |
| Robot Registration & service authentication | Broadcast to device sensing<br><br>Device registration | Robot-specific Registration<br><br>Information sharing<br><br>Authenticate Access to function handlers | |
| Atomic function orchestration | | Access & set up to function handlers | |
| Robot Grouping | Group Management Service Procedure for V2X [17] | Synchronization | |
| Environment Model Establishment | NR Positioning Protocol considers fusion of positioning-related information (GNSS, WLAN, Bluetooth, 3GPP, etc…) [18] | Multimodal Sensor fusion (i.e., sensor fusion between ISAC wireless signals and non-3GPP signals) at network or robots | Task specific spatial resolution<br><br>Update time<br><br>Computation capability |
| Sensing Adaptation | | Task specific updates e.g., sensing adaptation rate, modalities, sensing sources<br><br>Adapt Sensing Service Area per Sensing Modality (e.g., ISAC, camera, LIDAR, UWB, etc…) to cover changing blind spots | Refresh rate: {environment dynamicity, device capability} |

| Atomic function/handlers | Potential Functional requirements to support Use Case | | KPI Value Discussion |
|---|---|---|---|
| | Met in 5GS | Partially met/not met | |
| **Identification & Classification** | No | Object Identification and Classification with ISAC sensing signals from single or multiple sources<br><br>Fusion of object identification & classification using 3GPP or non-3GPP sensing information | AI/ML model split inference (5):<br><br>Max allowed uplink end-to-end latency: 2 ms<br><br>Reliability: 99.9% |
| **Perception Handler :** Object Perception | No | Get Object Characteristics (size, shape, material) with ISAC wireless signals<br><br>Get locations within object to perform grasping with ISAC wireless signals<br><br>Object Classification with ISAC wireless signals<br><br>Extended Object Target Detection with ISAC wireless signals (i.e., big object)<br><br>Network allow information sharing of ISAC wireless and non-3GPP sensing signals between robots | • Accuracy of Position Estimate: <0.5 m<br>• Accuracy of Velocity Estimate: 0.5 m/s<br>• Range Resolution: 0.5 m<br>• Velocity Resolution: 0.5 m/s<br>• Max Sensing Service Latency: <100 msec<br>• Wireless Communication (2): KPI Value<br>• Uplink: NA<br>• Downlink: NA<br>• Sidelink (unicast or groupcast)<br>• Data rate:  <1 Mbit/s per Robot<br>- Reliability:  99.9999 %<br>- End-to-end latency: 7 msec<br><br>*Note: table above assumes mobile robots, KPIs for e.g. manipulator robots may be more precise.* |

| Atomic function/handlers | Potential Functional requirements to support Use Case | | KPI Value Discussion |
|---|---|---|---|
| | Met in 5GS | Partially met/not met | |
| **Perception Handler :** Environment Perception | No | Estimate proximity to other objects in the operating environment with ISAC wireless signals<br><br>Network should enable in-network computing for Computational Offloading: On-board Sensors<br><br>Network-assisted Environment Perception with trusted 3rd-party applications | **Network-assisted Environment Perception** (Computational Offloading)<br>• Uplink (unicast or groupcast)<br>- 300-500 Mbits/s per Robot (one camera per Robot)<br>- Reliability: 99.9999%<br>- End-to-end Latency: 33 msec<br>• Downlink (unicast or groupcast)<br>- Data rate: <1 Mbit/s<br>- Reliability: 99.9999 %<br>- End-to-end Latency: 7 msec |
| **Task Handler:** Multi-robot Placement Plan | 5G system natively supports edge computing with MEC attached (3rd party application) to UPF (e.g., for placement plan computation) [16] NA<br><br>Positioning (1) | Object and environment model sharing<br><br>Network should enable in-network computing or with trusted 3rd-party applications for Computational Offloading at deep-edge | Low resolution map<br><br>Collision avoidance<br><br>High update frequency for accurate position & posture (object, human) detection [emergency obstacle avoidance] |
| **Task Handler:** Multi-robot Grasping Plan | 5G system natively supports edge computing with MEC attached (3rd party application) to UPF (e.g., for grasping plan computation) [16] | Executing reasoning/decision making to define actions over sidelink (unicast or groupcast)<br><br>Network should enable in-network computing or with trusted 3rd-party applications for Computational Offloading at deep-edge | High resolution map with high frequency updates<br><br>Force gain over multiple robots [8]<br>- Data rate: <1 Mbit/s per Robot<br>- Reliability: 99.9999 %<br>- End-to-end latency: 7 msec |

| Atomic function/handlers | Potential Functional requirements to support Use Case | | KPI Value Discussion |
|---|---|---|---|
| | Met in 5GS | Partially met/not met | |
| **Task Handler:** Multi-robot Path Plan | 5G system natively supports edge computing with MEC attached (3rd party application) to UPF (e.g., for path plan computation) [16] | Communicate & execute the computed global path plan<br>Network should enable in-network computing or with trusted 3rd-party applications for Computational Offloading at deep-edge | Accuracy requirement is scenario dependent |

**Justification (1):** 3GPP outlines this sensing service is required to detect objects (e.g., humans, tools) in vicinity. Wireless sensing can also be performed by network. Sensing with network introduces additional errors (due to compounding errors of two separate positions) [7]. However, robot may provide its position derived from other means (e.g. mono-static sensing, GNSS, positioning, UWB, IMUs, odometry).

**Justification (2):** Communication streams occur between robots with environment perception data (e.g., object(s) in environment detected/recognized with signal processing/AI/ML algorithms). Latency is low to minimize the time to reach consensus on environment, and communication reliability is high to enable reliable dynamic interaction and reactive object avoidance from shared sensing data [19].

**Justification (3):** for Network-assisted Environment Perception (Computational Offloading): Communication stream is raw video stream data in uplink (e.g., object(s) in environment detected/recognized with AI/ML algorithms at edge server) [19]. Control commands are sent in downlink. High communication reliability may be required to guarantee significant degrees of noise-free input to AI/ML methods operating in real-time which may be sensitive to noise.

**Justification (4):** AI/ML model distribution for image recognition. Required data rate will depend on the transferred AI/ML model (e.g., 1.1 Gbits/s for 138 Megabyte size model) [8]. Communication reliability is high even though some errors in model weight factors are permissible.

**Justification (5):** AI/ML model distribution for image recognition. Required data rate will depend on the AI/ML model and the splitting point [8]. Communication reliability is high for model topology (e.g., computation graph of a convolutional neural network) since mismatch in dimensions of input data and weight matrices can make model unusable.

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# Abbreviations

| | |
|---|---|
| 5G-ACIA | 5G Alliance for Connected Industries and Automation |
| AI | Artificial Intelligence |
| CAV | Connected and Automated Vehicle |
| 3GPP | 3rd Generation Partnership Project |
| 5GS | 5G System |
| 6GS | 6G System |
| IEEE | Institute of Electrical and Electronics Engineers |
| ITU | International Telecommunications Union |
| KPI | Key Performance Indicators |
| LIDAR | Light Detection and Ranging |
| ML | Machine Learning |
| NR | New Radio |
| PQoS | Predicted Quality of Service |
| R2R | Robot-to-robot |
| RDE | Remote or damaged environment |
| SAR | Search and Rescue |
| SOBOT | Service Robot |
| SL | Sensing Location |
| TR | Technical Report |
| UC | Use Case |
| WG | Working Group |
| WI | Work Item |

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