Networking for Cloud Robotics: a case study based on the Sherpa Project

Alessio Botta*+, Jonathan Cacace+, Vincenzo Lippiello+, Bruno Siciliano+, Giorgio Ventre*+

+*Department of Electrical Engineering and Information Technology*

University of Napoli Federico II, Napoli, Italy

**NM2 SRL, Napoli, Italy*

{firstname.lastname}@unina.it

***Abstract*—With the big advances of networking technologies Robots can finally be "always on". And, they can now use the almost unlimited computation, memory, and storage resources of large datacenters, overcoming the severe limitations imposed by on-board resources: this is the vision of Cloud Robotics. To make it true, however, network connection should be fast, reliable, and available, with more specific requirements depending on the application scenario. In this paper we investigate how the different network technologies can serve different application scenarios, focusing on a specific one in the framework of an European Project called Sherpa. Sherpa aims at developing a robotic platform to support search and rescue activities in hostile environments like the alpine scenario. We discuss its specific network requisites considering different kinds of data that have to be transported from and to the Cloud and the related requirements in terms of minimum throughput and maximum tolerated delays and losses. We present a possible choice for this specific application scenario and show results of measurements taken from a real network to support our choice.**

***Index Terms*—Cloud Robotics, Computer Networks, Network Performance**

I. Introduction and Related Work

Cloud Robotics aims at creating a new generation of robots, in which at least some of the resources in terms of computing power, memory, and storage is provided by the external Data Centers (i.e. the Cloud). Nowadays the robot systems are generally equipped with more and more sensing units to be rendered increasingly autonomous. The processing of data coming from the sensors can be very expensive in terms of energy (e.g. for the analysis of high-resolution videos captured by the HD cameras). The Cloud can then be used to offload these heavy tasks. Its wide availability of computational and storage resources appears to be almost unlimited and the necessary management effort of provision is minimal. The Cloud is actually ubiquitous and hence accessible from almost everywhere. It also operates on demand, according to the robots requests, provides economies of scale and facilitates sharing of data across systems and users.

In such a context it is crucial to identify the proper network technology to connect robots to the Cloud. Characteristics of the network connection such as performance, reliability, power consumption, etc. must be suited to the specific application scenario of the robot. In fact, every Cloud Robotics application has specific requirements according to which a different kind of connection should be considered.

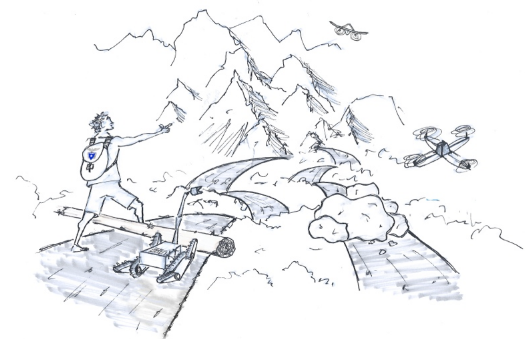

Fig. 1. A sketch of the SHERPA team [2].

Several different network technologies are available today in the scientific literature and on the market. In this paper we consider four of them, the ones we consider most suited for the Sherpa project [2] who aims at develop a mixed ground and aerial robotic platform for Search & Rescue (SAR) operations in alpine environment. We discuss their main characteristics and performance and then we compare them, providing details on the guiding factors that drove us to the choice of the best candidate for the project of interest.

A sketch of SHERPA scenario is depicted in Figure 1. In this context, a human operator collaborates with a heterogeneous robotic system to rescue survivor victims after avalanches. The robotic team is mainly composed of unmanned aerial vehicles (UAVs) with different characteristics and equipped with different types of sensors in order to retrieve information from the rescue scene and assist the rescuer during a mission. Finally, in the SHERPA vision, a swarm of many robotic teams might operate in parallel towards the achievement of a common task, like searching a missing person or patrolling a dangerous area, improving the capabilities achieved by a single team.

Unmanned Aerial Vehicles (UAVs) have been extensively employed in different applications such as industrial building inspection and surveillance [3], remote sensing and many others. As shown in [4] and [5], Search & Rescue operations can greatly benefit from the use of autonomous flying robots able to survey the operative environment and collect evidence about the position of a missing persons. Related to the SHERPA domain, different works (i.e. [7]) demonstrate the ability of a human rescuer to orchestrate a heterogeneous multi-robot system. Many research projects are pursuing cloud robotics developments, ranging from computing resources to systems architecture. An example is represented by the RoboEarth project, which envisioned "a World Wide Web for robots: a giant network and database repository where robots can share information and learn from each other about their behavior and environment" [8]. The possibilities to strongly improve robots performances are so evident, that a very fast integration of these new technologies is taking place. Recent successful applications include environment monitoring [9], manufacturing [10], and infrastructure inspection and maintenance [11].

In this paper, we firstly provide an overview of network technologies that can be used to connect robots to the Cloud, investigating their characteristics in terms of performance, constraints, coverage, etc. Afterwards, we introduce the European Project called Sherpa, which is the application scenario we identified and discuss how we selected the most suited technology for this specific project, considering also measurements from real networks. We finally end the paper with concluding remarks and future work.

II. Networks for Cloud Robotics

In the context of Cloud Robotics, Cloud Computing can be seen as the virtually unlimited brain robots can attach to, offloading all computational and memory intensive tasks as well as the large storage needs. Therefore, Cloud can provide a big boost in the Robotics field, as a possible solution to several problems that constituted a barrier to further development in the field [1]. It is then crucial to define the correct type of network connecting these systems to the Cloud and ensuring them with high performance and reliability. Such a network should firstly provide robots with a connection that is available and fully accessible during the whole duration of their work. That kind of concern is not secondary in a situation in which a wide range of possibilities, such as interferences and failures, must be taken in account. Secondly, it is necessary to define a network capable of meeting the different special needs of the robot or autonomous system it is meant for. Every Cloud Robotics application has its specific requirements, according to which a different kind of connection must be considered. It is also essential to pay attention to privacy and security issues, since a lack of them could dramatically compromise the system.

A. Network Characteristics and Performance

The first aspect of interest is network performance. Network performance are related to different parameters, which may be in contrast the one with the other or, in general, it may be difficult to maximize them all. In more details, network performance is typically evaluated considering three main parameters: bitrate, latency, and loss. The former parameter measures the amount of bits that can traverse a communication link or path from a source to a destination in a given time interval. It is typically measured in bit per second (or bps), with its multiples kbps, Mbps, Gbps, etc. The maximum bitrate a network technology can provide depends firstly on the physical transmission medium and the network technology used. The actual value attaining for a certain communication, instead, depends on several, time-varying factors such as the volume of network traffic already on the link, the possible traffic engineering policies enforced, etc.. The second parameter is latency, which measures the time elapsed from when the packet is sent to when it arrives to its destination. It depends on the network technology used and the network congestion. But, in contrast with the bitrate, it also depends on the physical distance between sender and receiver. Latency can also be measured two-way, in which case is called Round Trip Latency (or Round Trip Time). The third parameter is the loss, which occurs when one or more packets do not reach their destination because the are discarded along the path. The problem is typically caused by network congestion in wired networks, while it is more likely caused by interference in wireless scenarios. Other important aspects to consider include mobility, coverage, and reliability. Firstly, it is important to assess the mobility requirement, i.e. the necessity for the robot of moving or standing still, and the speed of movement in the former case. Secondly, the operating conditions of the networks are to be considered, e.g. if it has to work outdoor or indoor, its coverage in both cases, etc. We also have to consider that network (temporary) outages can make the system brainless. This has to be taken into account at system design time, considering the kind of network technology chosen, the outages expected, the possible countermeasures, and the possibility for the robotic system to operate autonomously during offline periods.

B. Network Technologies Considered

In the following, we introduce the basic characteristics of four network technologies we considered, as they are the most appealing for the Sherpa project.

1) Wireless LAN: In this section we concentrate on IEEE 802.11, also know as WiFi. IEEE 802.11 is a family of standards for wireless LANs that has spread very quickly and broadly in recent years. While the first variant, 802.11b, allowed bitrates up to 11 Mbps, the latest one available on the market, IEEE 802.11ac, allows bitrates up 6.77 Gbps. Latency and error rates can be high in wireless LAN technologies, because of fading, interference, etc. The real expected bitrate, latency, and losses are very difficult to be estimated because of their high variability with the specific deployment considered. IEEE 802.11 stations are generally connected through Access Points, even if ad-hoc connections, with no access points, are also possible. A typical access point has a signal coverage of about 20 meters indoors and a larger range outdoors, which can be up to 100 meters if there are not barriers such as walls, or trees.

2) Mobile Cellular: Mobile cellular network technology has evolved in recent years from the first GSM/GPRS standards, providing few Kpbs with very high latency and losses, to the fourth generation, Long-Term Evolution (LTE), a radio access technology able to provide mobile phones and data terminal with high-speed wireless communications [16]. LTE provides peak bitrates of 300 Mbps in downlink and 75 Mbps in uplink, latency in the order of few milliseconds, and very small loss values. As a drawback, like all other mobile cellular networks, it uses licensed band, increasing the costs, which can become too high for a big project with demanding requirements in terms of bandwidth. Moreover, the coverage is not ensured everywhere worldwide, antennas coverage is in the range of 3 km^2.

3) WiMAX: WiMAX is a family of wireless communication technologies based on the IEEE 802.16 set of standards. The 802.16 essentially standardizes two aspects of the network standard: the physical layer (PHY) and the media access control (MAC) layer. The WiMAX technology allows to deliver high-speed Internet connections to end-users. As a matter of fact, it has a maximum throughput of 75 Mbps, and a range of up to 30 km (compared with 50m for WiFi). Hence, it ensures higher data rates over longer distances, efficient use of bandwidth, and avoids interference almost to a minimum, with respect to other wireless technologies.

4) Satellite: Originally launched for long-distance telephony and for television broadcasting, communication satellites are more and more used today for Internet access [17]. Internet access via satellite has historically been chosen by users not served by other access networks, often in rural areas, or having special needs (e.g. bank communications). The first commercial services for residential satellite Internet access were monodirectional, requiring another technology (e.g. the telephone) for the uplink direction. Later on, bidirectional commercial services have been launched, but still their performance was poor and the costs high. In recent years, a great effort has been put on this technology and several improvements have been achieved. Among the most relevant, we cite the new TCP versions and improved TCP acceleration mechanisms, which highly increased the performance of TCP (and then of applications relying on it) over the satellite link and the launch of satellites with a set of features specifically designed for Internet access (e.g. multi-spot illumination/frequency reuse, robust terrestrial network based on MPLS). As a consequence, recent commercial services for Internet access via satellite promise tens of Mb/s user data rates and stable performance.

III. The SHERPA Project

The SHERPA project addresses the problems of surveillance and rescuing in unfriendly and hazardous environments, like the ones usually operated by civil protection, alpine rescuers and forest guards. Such environments are typically characterized by adverse terrain and weather conditions and should be efficiently patrolled while keeping costs and risks for human beings at reasonable levels. Within this context, the goal of SHERPA is to develop a robotic platform supporting the rescuers in their work and by improving their ability to intervene promptly. In this context, the activities of SHERPA are focused on a combined aerial and ground robotic platform suitable to support human operators in accomplishing Search & Rescue tasks in alpine scenario. The presence of unstructured and dynamically changing environments, require the capability of the robots to communicate each other in order to share salient information retrieved from the operative scene and properly assist the human rescuers. The following actors compose the basic SHERPA team:

- A *human rescuer*, who is an expert of the specific rescuing mission or surveillance activity. He continuously transmits his position and his healthy state to the robotic platform, while communicate with it relying on handy and easy-to-operate technological devices, which allow a fluent and effective interaction based on natural voice and gestures.
- Small scale *rotary-wing Unmanned Aerial Vehicles* (*UAVs*), equipped with cameras and *ARVA*[1] transceivers (*Avalanche transceivers*) used to support the mission by enlarging the patrolled area with respect to the area potentially covered by the human rescuer and speed up the search mission. Visual data and victim detection information are shared between the member of the team in order to act as a flying eye of the rescuer, helping him to inspect the surrounding area.
- A *ground rover* serves as a transportation module for the rescuer equipment and as a hardware station with computational capabilities. In order to improve the autonomous capabilities of the robotic platform, a multi-functional robotic arm is also installed on the rover.
- A *fixed-wing UAV* and an *unmanned helicopter* with long flight endurance, high-altitude and high-payload aerial vehicles, with complementary features with respect to the small-scale UAVs above introduced. Within the team, they are used for constructing a 3D map of the rescuing area, as communication hub between the platforms in presence of critical terrain morphologies, for patrolling large areas not necessarily confined in the neighborhood of the rescuer.

Collaboration and information sharing between all members of the team is necessary to assure the success of the rescue mission due to the limitation of each components of the robotic system. Specifically, the human rescuer is able to command the robotic system providing high-value inputs thanks to his experience in the field. On the other hand, the demanding rescuing activity and the considered hostile environment make the rescuer presumably busy and focused on the task to be accomplished, and thus unable to lead and supervise the team continuously. The ground rover serves as a carrying vehicle and docking station for the small-scale rotary-wing UAVs. It is characterized by remarkable autonomy, payload, and on-board calculation capabilities but it suffers of limitation in terms of ability of reaching wild areas and overtaking big natural obstacles. The incomparable capabilities of capturing data both in terms of visual and transceiver information of the small-scale UAVs due their privileged positions, high-maneuverability, hovering on hot targets, and following the rescuer in inaccessible (by ground) areas are counterbalanced from their limited autonomy and on-board low calculation

[1]The *Appareil de Recherche de Victims en Avalanche*

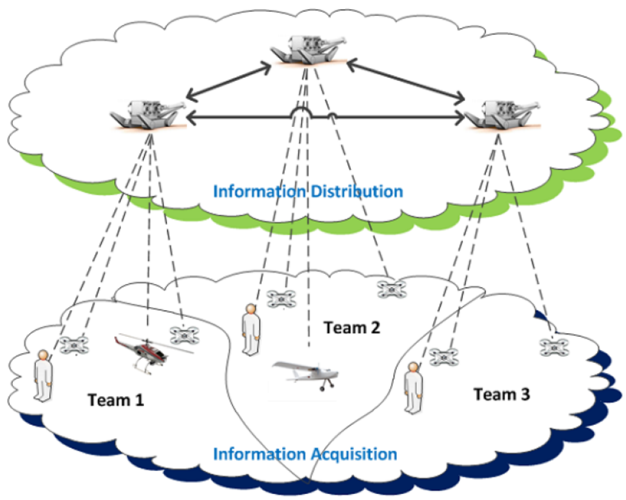

Fig. 2. Topology of the internal Sherpa network.

performance. This make their radius of action is quite limited. Finally, both the fixed-wing and the unmanned helicopter are characterized by high perception capabilities allowing them to patrol large areas with low energy consumption and remarkable payload and ability to fly in critical weather conditions respectively. On the other side, their configurations force these robots to fly at high altitudes and far from obstacles and human beings, allowing them able to exploits the captured high-altitude information to optimize and coordinate the local activities of the team and complement the low-altitude aerial capabilities of the small-scale rotary-wing.

IV. Finding the Most Suited Network Technology

The Sherpa project already uses a networking technology for interconnecting all the actors (drones, humans, etc.). This network, however, is intended for local communications, as shown in Fig. 2. Our aim, instead, is to provide the entire system with Internet access, so to be connected to the Cloud.

A. Network Requirements

The benefits of the introduction of Cloud Computing services in the Sherpa project are huge. For example, aerial vehicles could delegate the majority of their tasks to Cloud resources, using large datacenters to: access to extensive quantities of images, helping them with object recognition (e.g. natural elements of the alpine environment); elaborate and interpret the sensor data collected; exploit inference engines, with no problems of power consumption and CPU utilization; collaborate with humans for video and image analysis; store and retrieve large volumes of data regarding previous rescue missions (therefore allowing each unit to learn by its predecessors errors and findings), etc.

To reach this goal, it is firstly necessary to study the requirements of the Sherpa system when connected to the Cloud. Several technical issues have to be addressed, such as the bitrate, latency, and losses, the network coverage necessary for all the agents to be connected, the speed at which they move, etc.. We noticed that the system is already provided with an internal network. This means that the communication with the Cloud may be managed by a single central element (maybe the Sherpa box), with less requirements in term of mobility. In this scenario each actor of the Sherpa team would send the data that need Cloud computation, analysis, or storage to the central agent, which will act as a relay to the Cloud. After being brought to the area of the accident, the central node may then act as a gateway for the Sherpa team towards the Internet, moving slowly, just to follow possible major shifts of the team.

It is then necessary to analyze the volume and type of data traveling over this connection. Data involved in this project is of various types, such as, for example: Detailed maps and 3D reconstructions of the area, to allow drones and other vehicles navigation; GPS and localization information in order to communicate it to the central agent, to other members of the team, or to the human rescuer if they spot something; HD video and images to be analyzed to look for signs of human presence, to detect dangerous situations and potential risks, etc.; Outcomes, assumptions, and information inferred by each agent; Weather conditions; etc..

A similar pool of information is surely of a large size. Therefore, an important requirement of the network is high bitrate. In particular, we should consider a network technology as a possible candidate only if it provides a minimal bandwidth of 4 or 5 Mbps (which is the esteemed bitrate of a HD video, the most demanding kind of data exchanged with the Cloud), but a higher bitrate (e.g. 15, 20 Mbps) is required if more than one unit is sending this kind of information over the network. As far as the latency is concerned, the first evaluation to make is whether the system has real time constraints or not. If we assume that the Sherpa fleet must immediately react to external stimulations and inputs, we are then adding real time constraints to the communications, and latency must be kept as low as possible. In particular, ideally, latency should be bound to a maximum of 10/50 ms. But this is actually true only for communications that remain within the internal network. A higher latency is acceptable for Cloud communications, where more intensive computations are performed, to augment information available locally. As for packet losses, they are not acceptable especially when maps, GPS information, agent findings and rescuer inputs and commands are traveling over the network. If instead data is represented by HD images or video, a small loss can be accepted, e.g. smaller than the 1% in order not to undermine the analysis and the recognition operations. Regarding power consumption caused by the network connection, the Sherpa box would be the component connected to the Internet and, since it does not participate in moving, rescuing, and searching tasks, a higher battery consumption is allowed. Last issue to be considered is the cost. Using licensed band can be prohibitive due to high costs. Moreover, using a technology that is not widespread, can be more expensive and less reliable compared to the established standards as we cannot benefit of economies

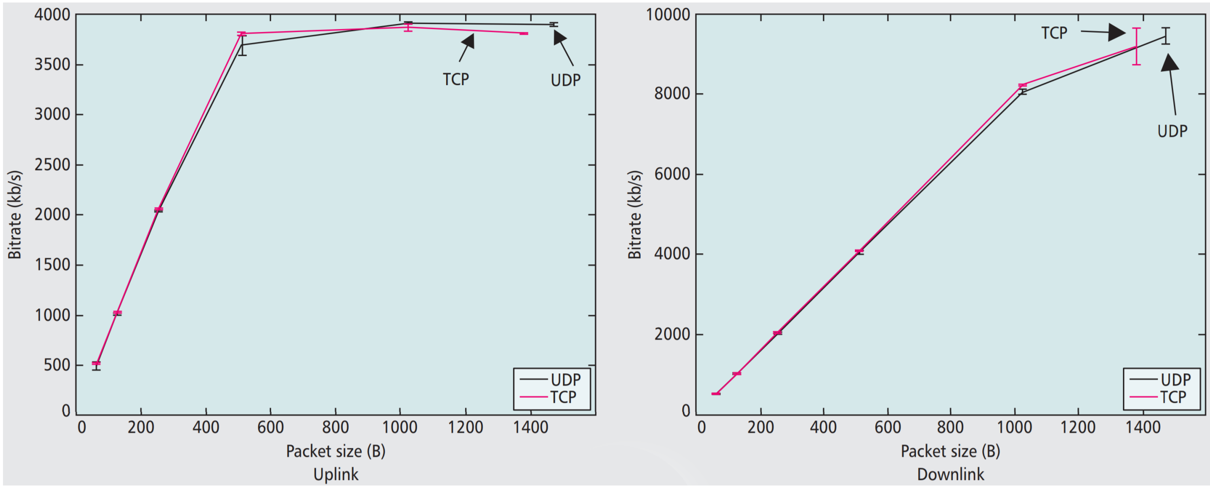

Fig. 3. Bitrate measured on the Satellite links [19]

of scale and large testing bases.

B. Chosing the Most Suited Technology

Given the requirements reported in previous section, in this section we evaluate which of the (wireless) technologies presented in Sec. II would best suit the Sherpa project. The Wi-Fi standard can immediately been discarded, as it is clear that we need a wide area network (WAN) connection. As for mobile cellular, the LTE would have been preferred to the HSPA as it provides a higher bitrate. However, also the LTE technology can been disregarded for different reasons. First of all, for its coverage: to connect to a LTE network one should be in proximity of an antenna, which can usually cover areas of 3 km^2. Moreover, we empirically verified that the LTE only covers a small portion of the alpine region. Costs would also be very high because LTE operates on licensed band and the fees are volume-based, which does not suit continuous HD video transmissions necessary for this project. As far as the WiMAX is concerned, we have problems similar to the previous technology: a provider should ensure IEEE 802.16 coverage in the whole alpine region, which would require placing several WiMAX base stations. This is at least very costly, if feasible.

The most efficient and effective solution seems then to be the satellite technology. It could provide our team with sure coverage in the whole alpine area (but also everywhere else, in case the Sherpa team has to be employed in other scenarios). The following operational organization should be set up with this technology: the Sherpa box (or a ground rover provided with some on-board intelligence) should remain in a central position with respect to the operating zone of the team. It should be provided with a parabolic antenna, a satellite modem, and a system to automatically point the dish to the satellite. Slow movements would be allowed thanks to the pointing device, which would constantly ensure the correct orientation of the antenna.

To verify this assumption, however, the performance of this technology should be analyzed. We conducted studies on recent satellite technologies [18], [19] to empirically analyze the performance of latest satellite Internet connections. In particular, a two-year-long study has been conducted, in collaboration with one of the main satellite operators in Europe, in order to evaluate the performance of two different generations of this technology. We call them First Generation Satellite (FGS) and Second Generation Satellite (SGS) in the following. The former represents the first bidirectional Internet service and the latter is the latest generation, including several improvements, as reported in Sec. II-B4. Below we report the most interesting results of these studies. We focus our attention on SGS because it represents the best candidate for the Sherpa project.

As far as the bitrate is concerned, 100 rounds of measurements have been made in different days and daytimes between 2013 and 2014. Their averages have been plotted as a function of the packet size, for both TCP and UDP. Results in Fig. 3 show that the uplink bitrate is about 3.9 Mbps and downlink bitrate is about 9.5 Mbps, both with UDP and TCP. The similar performance observed by the two different protocols is due to the fact that SGS i) uses TCP performance accelerators, and ii) had, at the time of measurements, a small number of users since it was still quite new.

Latency is surely the most critical parameter for a long-distance wireless network such as the satellite one. In the works we are considering ([18], [19]) it has been calculated as one way delay, since the RTT depends on both uplink and downlink directions which we know to be asymmetrical in this context. To overcome the clock synchronization issue, packets were received by the same hosts that generated them using an intermediate NAT device. The latency measured, see Fig. 4, is about 300 ms with UDP, and ranges from 300 ms to 600 ms for TCP. As shown, TCP latency can be reduced using larger packets, which would allows us to also use TCP if needed.

The authors of [19] tested if real users were satisfied when

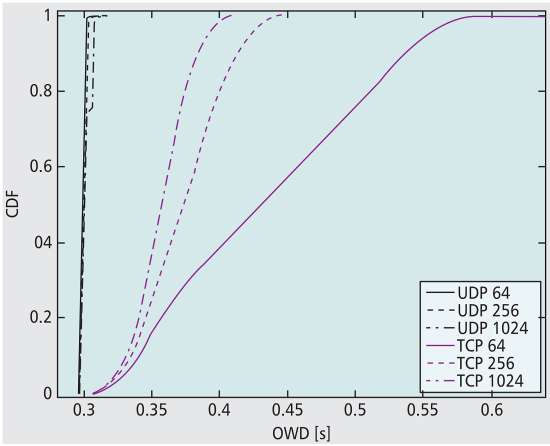

Fig. 4. Cumulative Distribution Function (CDF) of One Way Delay (OWD) measured on the Satellite links [19]

	Audio		Video	
	Average	Standard deviation	Average	Standard deviation
FGS	4.25	0.84	2.55	0.64
SGS	4.35	0.74	2.72	0.67

Fig. 5. MOS measured on the Satellite links with real applications [19]

using Skype. This is of interest for us as Skype is very demanding in terms of latency and is an example of real time application. In these tests, Skype was used both for only voice calls as well as for voice and video calls. People were asked to give an evaluation (with a number between 1 and 5) of the service provided. This evaluates the so called Mean Opinion Score (MOS in brief). As Fig. 5 shows, the marks were very high for only voice calls (with an average of 4.35). The evaluation was instead lower for voice and video calls (with an average of 2.72). This would cause issues to our system when sending HD video. Anyway, as previously mentioned, the system does not have real-time constraints for HD video analysis. Therefore, we can assume that this result will not represent a problem for our application.

Concluding, this analysis shows that the satellite technology could be successfully deployed for what we believe to be an extremely interesting extension for the Sherpa project. Letting the Sherpa team exploit the Cloud potential could, in fact, enhance an already well-designed system, lightening the load of work required to each member and tapping the huge knowledge that is stored in the Cloud.

V. Conclusion and Future Work

In this paper we presented a case study for Cloud Robotics based on the Sherpa European Project. We analyzed several different networking technologies that can be used for connecting the devices and operators involved in this project to the Internet so to benefit of the huge computational power, memory, and storage of the Cloud. We studied the requirements of the different communications involved in the project activities and discussed if and how such requirements can be satisfied using the different network technologies considered. We proposed the use of satellite Internet services, which best suit the project requirements. We also reported reported the results of an experimental study of the performance of this technology to better understand their potential in the real of Cloud robotics.

We believe that this paper represents a useful case study for researchers interested in this promising field.

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