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Collab-SAR: A Collaborative Avalanche Search-and-Rescue Missions Exploiting Hostile Alpine Networks

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ABSTRACT Every year, Alpine experiences a considerable number of avalanches causing danger to visitor and saviors, where most of the existing techniques to mitigate the number of fatalities in such hostile environments are based on a non-collaborative approach and is time- and effort-inefficient. A recently completed European project on Smart collaboration between Humans and ground-aErial Robots for imProving rescuing activities in Alpine environments (SHERPA) has proposed a novel collaborative approach to improve the rescuing activities. To be an integral part of the SHERPA framework, this paper considers deployment of an air-ground collaborative wireless network (AGCWN) to support search and rescue (SAR) missions in hostile alpine environments. We propose a network infrastructure for such challenging environments by considering the available network components, hostility of the environments, scenarios, and requirements. The proposed infrastructure also considers two degrees of quality of service, in terms of high throughput and long coverage range, to enable timely delivery of videos and images of the long patrolled area, which is the key in any searching and rescuing mission. We also incorporate a probabilistic search technique, which is suitable for collaborative search assuming AGCWN infrastructure for sharing information. The effectiveness of the proposed infrastructure and collaborative search technique, referred to as *Collab-SAR*, is demonstrated via a series of computer simulations. The results confirm the effectiveness of the proposal.

INDEX TERMS Air-ground collaborative wireless network, alpine scenarios, unmanned aerial robots, unmanned ground vehicles, WiMAX, α-level probabilistic search technique.

I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

The marvelous natural beauties of Alps embrace around 120 million tourists every year [1]. This count increases rapidly as winter tourism continues gaining enormous popularity. On the other hand, snow avalanches are very active geomorphic process in the Alpine environments. Occasionally, tourists and rescuers may catch the avalanche that can claim their lives or often injure them. According to the statistics [3], around 100 people lost their lives each year in the Austrian, French, German, Liechtenstein, Italian, Slovenian and Swiss Alps during the last four decades. More specifically, from 1950 to 2015, 3729 people lost their lives due to avalanches in the Austrian, Swiss and Slovenian Alps, and from 1970 to 2015, 4750 people lost their lives in the European Alps [3]. The frequency of avalanches in Alpine environment can be predicted from the annual reports by the WSL Institute for Snow and Avalanche Research SLF [2].

As a consequence, rescue activities in this hostile environment have been considered as an important issue for the last couple of decades. Several new technologies and improved avalanche safety equipments as well as rescue methods were proposed, which have allowed a faster response compared to those of several years back. However, most of these technologies are still not yet capable of responding as rapidly and accurately as demanded, mainly due to their non-collaborative characteristics. Consequently, tourism authorities and researchers are continuously looking for more advanced alternatives.

With the vision of reducing the number of fatalities in the Alpine environment, a European project on Smart collaboration between Humans and ground-aErial Robots for imProving rescuing activities in Alpine environments (SHERPA) was carried out in 2013–2017 [4], [5] to investigate the feasibility of an Air-Ground Collaborative Wireless Network (*AGCWN*) to speed up the rescue missions. The underpinning search is *time-critical*, which envisages an efficient collaborative search effort on the top of *AGCWN* platform that is expected to lower the search time.

B. STATE OF THE ART

There exists extensive literature on designing infrastructure for wireless mesh, ad-hoc and sensor networks [6]–[17]. For instance, the recent advances in industrial wireless sensor networks (WSNs) towards the IoT-enabled efficient management systems was proposed in [6], whereas the dynamic infrastructure for efficient communications in WSNs was presented in [10]. In [11], an infrastructure was proposed for newly introduced crowd associated network. Moreover, infrastructures for wireless mesh networks and a wireless communication network for advanced metering were proposed in [16] and [17]. A major drawback of these wireless infrastructures to deploy in the hostile Alpine environment is their limited communication range, which prevents rapid target discovery and corresponding rescue actions.

In a smaller scale, the issues of enabling sensor communications among ground vehicles have been considered in [18] where a ZigBee-based network infrastructure was proposed. However, due to the limited vicinity and limited bandwidth of sensor nodes, this proposed infrastructure may be unable to assure any degree of *QoS* necessary for the *AGCWN*.

The aforementioned infrastructures are mostly relevant for ground-based networks, which limit the operation up to two-dimensional space. Beyond these, there exist a number of studies that investigated the design and development of network infrastructures for *Unmanned Aerial Robots (UARs)* [19]–[22]. Similarly to the ground-based networks, the capability of *UARs* networks is limited to aerial operation, which may not consider the issues of ground signal propagation. Remark that the infrastructure that was envisioned within the *SHERPA* project for rescue missions has two degrees of challenges, arising from the collaboration of both air- and ground-based wireless networks.

In [23], an air-ground sensor network has been proposed for crop monitoring. Due to the limited-range and limited-bandwidth of the sensor nodes, this proposed network may not be able to deliver time-critical information during the search and rescue activities. In [24] and [25], two other network infrastructures were proposed for urban environment and surveillance networks, respectively. However, since the issues, challenges, and network components are unique in *SHERPA* project due to the harsh/unfriendly environment, these network infrastructures are also not portable to *AGCWN*.

A limited number of works have partially considered the design and development of a reliable network infrastructure for the rescue mission in Alpine environment. Rahman [26] argued to employ *WiMAX* technology, which enables long range communications. On the other hand, Rahman [27] only considered a restricted collaboration, namely intra-team communication, among all the rescue agents. To speed up a rescue mission, inter-team communication is also mandatory, which has been lacking from the previous works on communication platform for Alpine rescue missions. Inter-team communication is anticipated to improve collaboration by exchanging critical information and preventing redundant overlapping search areas, which in turn reduces the overall search time and enables timely assistance to the casualties.

C. CONTRIBUTIONS OF THIS WORK

In this paper, we propose *Collab-SAR:* A collaborative avalanche search-and-rescue technique that includes a wireless-based network infrastructure and a collaborative search technique. The wireless-based network infrastructure referred to as *AGCWN* is proposed with the objective of enabling wireless communications among *Human Rescuers (HRs)*, *Unmanned Aerial Robots (UARs)* and *Unmanned Ground Vehicles (UGVs)* as envisioned by the SHERPA project. The *AGCWN* architecture considers the available network components, hostility of the environments, scenarios and requirements. Embedded within the network platform, both intra-team and inter-team communications are considered with a realistic path-loss model which was absent in the previous literature of Alpine rescue missions. Leveraging upon the proposed *AGCWN* and support for both intra- and inter-team communications, a collaborative search technique is proposed with the aims of preventing redundant overlapping searches among different teams and thereby speeding up the discovery of targets (i.e., avalanche victims). Among all the existing searching techniques in the literature, it has been demonstrated that the *Bayesian Search*—a.k.a., *Probabilistic Search Technique (PST)*—is a good candidate for *SAR* activities [28]–[33]. In this paper, we propose a variant of the PST, which specifically relies on the unique collaborative structure of the proposed network for sharing information.

The rest of the paper is organized as follows. Since we consider the avalanche rescue missions in Alpine environment, a brief introduction of the environment along with expected communication agents, scenarios and requirements is given in Section II. Section III discusses the proposed *AGCWN* infrastructure by considering the inputs from Section II. The proposed search technique is detailed in Section IV. Section V provides the performance evaluation of both the proposed search technique and network infrastructure using extensive numerical simulations. Finally, Section VI concludes the paper by summarizing the key contributions.

II. OVERVIEW OF THE ALPINE NETWORK

For the sake of completeness, this section briefly outlines the network components, scenarios and requirements of *AGCWN* for human rescue activities in Alpine environment. The discussion is mainly based on [4] and [27].

A. NETWORK COMPONENTS

The Alpine search and rescue network comprises multiple components, namely *UARs*, *UGVs* and *HRs*. A collaborative effort of these components is expected to assist in facilitating rapid response and accurate rescue actions in the challenging Alpine environment. These components are briefly discussed below:

1) UNMANNED AERIAL ROBOTS (UARS)

Two categories of *UARs* are employed in the *AGCWN* to gather videos and images of the patrolled area, namely: i) Short-Range *UAVs* (*SRUs*), and ii) Long-Range *UAVs* (*LRUs*).

The *SRUs* are typically equipped with image capturing devices and relevant sensing devices. Every *SRU* has limited on-board intelligence, limited area of coverage, limited autonomy, and is supervised by the rescuer as if they are the "*flying eye*" of the rescuer. These *SRUs* support the rescue and surveillance mission by enlarging the patrolled area through enabling remote access to the impassable areas. Multiple *SRUs* can be simultaneously deployed to boost the efficiency of a mission.

On the other hand, the *LRUs* are equipped with high-definition video and image capturing and sensing devices that enable information gathering of a large patrolling area. Two types of *LRUs* are employed in the rescue mission, i.e., i) *LRU* Rotated Wing (*LRU-RW*), and ii) *LRU* Fixed Wing (*LRU-FW*). *LRU-RW* has remarkable payload carrying capabilities and ability to fly in critical weather conditions. On the other hand, *LRU-FW* can be characterized by unmatched eagle-eyed capabilities that allow to patrol large areas with limited energy dissipation. The coverage radius of these devices are confined within the neighborhood of the rescue area. All information captured by *LRUs* is exchanged with unmanned ground vehicles to coordinate and optimize the rescue mission, and complements the aerial capabilities of *SRUs*.

2) UNMANNED GROUND VEHICLES (UGVS)

The *UGVs* are considered as the *Base Station (BS)* of this communication paradigm since each *UGV* acts as a primary access point for the rest of network components. They have the ability to reach wild areas and are capable of overtaking natural obstacles. Each vehicle carries a *SHERPA box*, which contains: i) communication and computation hardware, ii) docking/recharging station for *SRUs*, and iii) storage for *HRs*. Every team on a rescue mission comprises at least one *UGV*. In addition, the *UGVs* in different teams can communicate with each other to enable inter-team communications, which is critical for a rapid and accurate rescue mission.

3) HUMAN RESCUERS (HRS)

Similarly to any existing rescue mission, the *HRs* play the most important role to coordinate the activities and deliver the much needed aid and reliefs. In the context of Alpine network, the *HRs* may carry the *SHERPA box*. Each *HR* obtains information from the robots that are involved in the mission. Each *HR* can also communicate with the other *HRs* utilizing the *SHERPA box* or through nearby *UGVs* to accomplish the team goals. When victims are discovered, the nearby *HRs* attempt to rescue them.

B. SCENARIOS

Figure 1 presents a glimpse of the hostile Alpine environment with inherent physical obstacles and slopes. Unfavorable weather conditions (e.g., snowfall, wind, fog and rain) can further limit the network operation in terms of mobility of rescue agents and wireless connectivity. In the following we distinguish two main scenarios typically encountered during the current search and rescue activities in Alpine environment.

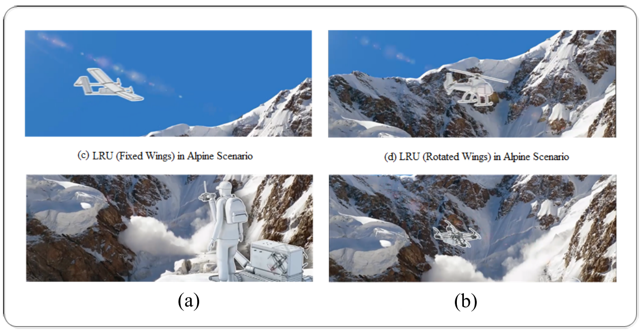


FIGURE 1. Network components in alpine environment. (a) LRU (Fixed Wings) in Alpine scenario. (b) LRU (Rotated Wings) in Alpine scenario. (c) HRs and UGVs in Alpine scenario. (d) SRU in Alpine scenario.

1) WINTER SCENARIOS

These scenarios can be further divided into: a) scenario without avalanche, and b) scenario involving avalanche. In the former scenario, the tourist may lose their way back to the resort or may fall in some accidents other than an avalanche, e.g., slip, unfavorable weather, etc. A trivial rescue mission

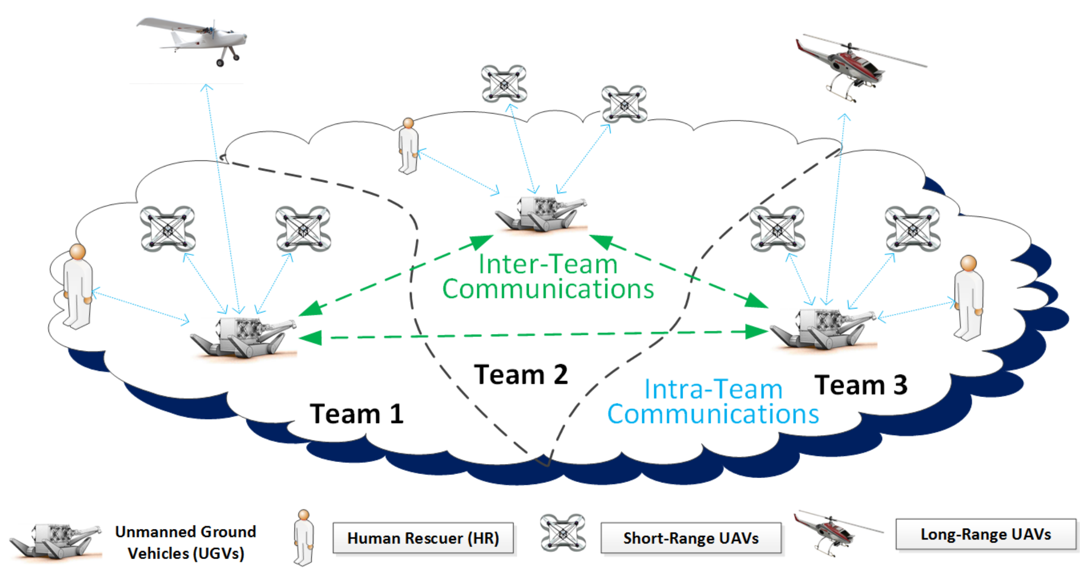


FIGURE 2. The architecture of the alpine network.

involving *HRs*, *UGVs* and *SRUs* are adequate for this type of scenario. In the latter scenario, most of the avalanche rescue missions are currently conducted through manned helicopters with each usually carrying a doctor, typically two-three rescuers and a dog unit. Based on the examination of a targeted area, the rescuers endeavor to discover an approximate spot and calculate the risk factor before landing. Once the rescuers are deployed within the targeted area, the helicopter starts scanning the area with an *ARTVA* device (i.e., equipment, security personnel and apparatus for avalanche accident) to speed up the mission. However, the helicopters can unfavorably cause noise and movement of snow, which in turn may hide possible evidences (e.g., gloves, clothes, jackets, etc.), and release gasoline molecules, which may interfere with the dog's sense of smell. Consequently, the *SHERPA* project was launched to find an alternative to the current solution by employing *HRs*, *UGVs*, and *UARs*. Moreover, by exploiting its inherent collaborative feature, the devised searching strategy is expected to be effective in mitigating the number of fatalities.

2) SUMMER SCENARIOS

A typical rescue mission in the summer season involves around 4-5 people inspecting a pre-assigned area on foot for a few hours and searching in the selected area just by sight. The altitude gap they have to inspect ranges around ± 800 m to ± 3 km. The surface to be scanned is determined based on the number of rescuers, the types of terrain and the probability to find the person in a given area. Regular electronic systems that are employed to find buried people in the snow following an avalanche such as *ARTVA* and *RECCO* are not typically used in the summer period since they are particularly developed for the winter environment. In such a situation, an air-ground collaborative communication network may offer a promising solution.

C. NETWORK REQUIREMENTS

Based on the environmental conditions and diversity of the rescue agents, the requirements of the Alpine network according to the *SHERPA* project are outlined as follows [26]:

- An expected higher mobility level of the *UARs*, which is in fact around 30 m/s for *LRUs*, 10 m/s for *SRUs* and 1.5 m/s for *UGVs*;
- Maintaining connectivity among all the actors involved in the search and rescue mission, which roam within a few miles from one another;
- Expected adequate data rates to support real-time video streaming and/or image transfers;
- A lower latency requirement for all the real-time data;
- A significant saving of energy dissipation to extend the lifetime of the robots;
- Flexible operating frequency band to offer communications resilience against unfavorable conditions;

Attenuation-aware

- network architecture considering wireless signal fading and fluctuations in foggy and rainy environments.

III. PROPOSED NETWORK ARCHITECTURE: AIR-GROUND COLLABORATIVE WIRELESS NETWORK (AGCWN)

When an avalanche accident occurs, multiple rescue teams are deployed based on the intensity of the accident. On a rescue mission, intra-team communications are essential to synchronize their operation whereas inter-team communications are equally important to optimize the overall rescue mission. We therefore propose an AGCWN infrastructure that is depicted in Figure 2 and discuss its architecture and implementation below.

TABLE 1. Challenges of the alpine network and the existing wireless standards.

	Standards				
Challenges	**WiFi**	**XBee**	**LTE**	**ZigBee**	**WiMAX**
Data Rate (maximum)	150 Mbps	250 Kbps	326 Mbps	250 Kbps	134 Mbps
Coverage (maximum)	250 m	1.6 km	5 km	150 m	up to 30 miles
Mobility Supported	Yes	Yes	Yes	Yes	Yes
Low Latency	Yes	No	Yes	No	Yes
Reduced Energy Expenditure	Yes	Yes	Yes	Yes	Yes
Unlicesed Operating Bands	Yes	Yes	No	Yes	Conditional
Diffusion	Yes	Yes	No	Yes	Yes

A. NETWORK ARCHITECTURE

Our proposed Alpine network architecture comprises two tiered services, namely: *i*) information acquisition tier, and *ii*) information distribution tier. In the first tier, all the actors involved in the mission acquire information of the patrolled area. In the second tier, those actors attempt to deliver their acquired information to the *BSs*, i.e., the *UGVs*. To fulfill its requirements, an actor can inquire the accumulated data from the *BSs*. This information exchange is only possible if intra-team communications are enabled. With further enabling collaborative data sharing among the teams via the *UGVs* (i.e., inter-team communications), the rescue mission can be optimized in terms of minimizing victims localization time, which in turn facilitates rapid and effective rescue actions.

B. TOPOLOGY

Network topology is a schematic description of the arrangement of a network that includes its nodes and connecting lines. To enable both intra-and inter-team communications, we propose a two-tier based unique topology that is the union of mesh and star topology. The first-tier enables intra-team communications under which all the intra-team components are connected via the *UGVs*.

The second-tier enables inter-team communications through the *UGVs*, i.e., all the *UGVs* are connected with one another, establishing a mesh topology. This tier is the backbone of the whole network and enables all the actors to collaborate one another to accomplish the final goal of a search and rescue mission.

C. TECHNOLOGY SELECTION

Given the network topology in Figure 2 and hostility of the environment in Section II, we summarize in Table 1 and discuss in the following the challenges associated with selection of technology to enable communications among the actors of interests.

1) DATA RATE AND LATENCY

In the *AGCWN*, a large proportion of actors acquire and exchange real-time videos and images. To enable such a real-time data exchange in the network, an adequate data rate (e.g., at least 500 Kbps) must be supported by the adopted wireless technology. Among the existing commercial wireless technologies, *ZigBee* and *XBee* are unable to satisfy the requirement since their maximum possible data rates are only 250 kbps, whereas the other standards listed in Table 1 may comfortably meet the requirement. In an effective rescue mission, videos and images must be timely exchanged among the actors. Therefore, along with a higher data rate, low latency is another QoS metric that must be strictly guaranteed. In Table 1, current wireless standards that attain higher data rates also support for low latency requirements, and they are therefore preferred for the *AGCWN*.

2) COVERAGE

As mentioned in Subsection II-C that the patrolled area can range around several miles. For this reason, the coverage area of the *AGCWN* should be more than or equal to the patrolled area in which Line-Of-Sight (LOS) transmission may not always be possible. Therefore, along with long-distance transmission coverage, the selected standard should support *Non-LOS (NLOS)* communications. This specification appears to be another critical issue in selecting a suitable technology among the existing wireless standards. For instance, IEEE 802.11 and *ZigBee* support vicinity of around 250 m and 10–150 m, respectively, whereas *XBee*, *LTT*, and *WiMAX* can cover a distance of more than a mile.

3) MOBILITY

For deploying an effective *AGCWN*, it is necessary to properly address the mobility issues since almost all the rescue agents are non-static with diverse mobility dynamics. Some agents such as *HRs*, *UGVs* and *SRUs* move at a low speed, whereas other agents such as *LRUs* may move quickly up to around 30 m/s.

Unlike the typical two-dimensional ground vehicular movement pattern, the overall mobility dynamics of the *AGCWN* nodes spans three dimension since the network lies between air and ground. All the standards in Table 1 may need reconfiguration in terms of their individual components (e.g., specific uses of antenna pattern) to support the required three-dimensional mobility model of the Alpine network.

4) REDUCED ENERGY EXPENDITURE

Energy remains one of the important issues in any isolated and hostile network environment where there is minimum supply of energy sources. Most of the components in the *AGCWN* are therefore battery powered. To extend the component lifetime and hence, the lifetime of the network, it is necessary to reduce energy expenditure and selecting energy efficient components is crucial in the implementation.

5) OPERATING BAND

Another important factor in selecting a particular wireless standard for the *AGCWN* components is the operating band characteristics since operation in a licensed band incurs a license cost. A cognitive radio concept can be built on top of a given standard to allow unlicensed users opportunistically exploit temporarily unused portions of the licensed band [12], [34], [35], [40]–[44]. This approach may facilitate operation within a licensed band with a significantly reduced cost. An alternative solution can be sought by using standards that operate over unlicensed bands, e.g., the Industrial, Scientific and Medical *(ISM)* frequency bands (especially around 2.4 and 5.8 GHz). However, this solution must be carefully examined with consideration of provision to data rate (i.e., ability to manage a large volume of data), coverage (i.e., ability to have a large coverage), resistance to noise and ability to manage interference.

6) DIFFUSION

The diffusion of a standard brings many benefits. When a standard is popular, we can safely assume that it has been tested rigorously in various scenarios and hence its weaknesses and strengths are well known. The availability of the devices in the market would be higher and they are also economically more affordable and reliable from a functional point of view. Consequently, diffusion could be another influential factor in selecting an appropriate wireless standard.

As further observed from Table 1, WiMAX appears to be the most suitable candidate of all the standards for the Alpine network. Moreover, it has a number of attractive features for the *AGCWN*, namely flexibility (i.e., both point-to-multi point and mesh systems), security (i.e., using techniques for encryption, authentication and measure against intrusion), management of *QoS*, high throughput (i.e., using the modulation schemes defined by the IEEE 802.16), ease of installation, mobility, low cost and wide coverage.

IV. PROPOSED SEARCH TECHNIQUE: EXPANDING NEIGHBORHOOD SEARCH TECHNIQUE (ENST)

The *Probabilistic Search Technique (PST)* [28] has been widely used for searching and localizing lost objects. It has been adopted in many *Search-And-Rescue (SAR)/Avalanche Search-And-Rescue (ASAR)* operations, including finding the lost sea vessels such as the USS Scorpion [29] and aircrafts such as the Air France Flight 447 [30] ad Malaysia Airlines Flight MH370 [31]. Integral within the *PST* is the *Probability Distribution Map (PDM)*—a map that contains the probability values of a target (targets) presence in various locations within the overall search area—which is maintained by every team involved in the rescue activities.

Since our proposed *Collab-SAR* envisions a collaborative effort and yet, most of the existing *PST*-based techniques are non-collaborative, a considerable amount of modification to the classical *PST* is obligatory. Although the use of *PDM* remains similar to that of classical *PST*, the updating process of this map takes advantages of the collaborative rescue effort. In the following we discuss necessary modification of generating *PDM* in *Collab-SAR* and three variants of *PST*, which highlight key differences of exploiting collaboration in the Alpine search activities.

In the traditional non-collaborative *PST*-based techniques, a team will consider any rescue area as a contiguous location. In this case, when multiple teams are employed on a rescue mission, their coverage area may overlap with each other. In order to avoid the redundant searches due to overlapping search area, in the *Collab-SAR* proposal, we divide the rescue area into multiple grid cells. A team can start searching from a predefined cell—that can be determined using several parameters, such as *Last Known Position (LKP)*, *Point Last Seen (PLS)*, and so forth—or a non pre-defined (i.e., randomly selected) cell. If the target is not discovered after completing the search in the current cell, the team moves to the next cell.

An efficient next cell selection algorithm can potentially lower the discovery time and thus, enhance the performance of the rescue mission. To achieve this objective, we propose an α-level, $\alpha \in \mathbb{Z}^+$, neighborhood searching strategy. Unlike most of the *PST*-based techniques, in this strategy, a search is conducted from 1-level neighborhood to α-level neighborhood to select the next cell. The searching operation is performed in an expanding fashion, i.e., it starts from 1-level neighborhood and ends at α-level neighborhood; and hence, called *Expanding Neighborhood Search Technique (ENST)*. This operation selects the cell with the highest probability of having the target point residing within the search region. Herein an optimum value of α is important to attain superlative performance of the proposed strategy.

After selecting the next cell, the proposed *ENST* calculates the new probability of the current cell before leaving it and shares this new probability value with all the other teams as detailed in Section IV-A. A pseudocode of the proposed technique is given in Algorithm 1. As observed from the algorithm, when all the cells have already been visited until α-level neighborhood, then a random cell is selected within a pre-determined range. Furthermore, if the target point is not detected after visiting all the cells, which may occur because of the detection error, the teams then start a fresh *Collab-SAR* mission.

A. RECURSIVE BAYESIAN ESTIMATOR

Recall that when the target is not detected within the current cell, the probability of the current cell is revised before leaving it and is then shared with the other teams. The revision of the probability is performed using the *Recursive Bayesian Estimator (RBE)* [32], which takes a series of observations into consideration.

Algorithm 1 Expanding Neighborhood Search Technique (ENST)

```
COMMENT: x → previous x-coordinator, x' → new x-coordinator, y → previous y-coordinator, y' → new y-coordinator, hx → highest x-coordinator, hy → highest y-coordinator.

Input parameter: x, y, x', y', hx, hy, IGS[hx][hy], α
Global parameter: P[hx][hy], S[hx][hy]
μ ← 0, x' ← −1, y' ← −1, hx ← 100, hy ← 100
assert(α > 0)
for δ ← 1 to α do
    for j ← −1 ∗ δ to δ do
        if y + j ≥ hy or y + j < 0 or x + δ ≥ hy or x + δ < 0 then
            continue
        else
            if P[x + δ][y + j] ≥ μ and S[x + δ][y + j] == false then
                x' ← x + δ
                y' ← y + j
                μ ← P[x'][y']
            end if
        end if
    end for
    for j ← −1 ∗ δ to δ do
        if y + j ≥ hy or y + j < 0 or x − δ ≥ hx or x − δ < 0 then
            continue
        else
            if P[x − δ][y + j] ≥ μ and S[x − δ][y + j] == false then
                x' ← x − δ
                y' ← y + j
                μ ← P[x'][y']
            end if
        end if
    end for
    for j ← −1 ∗ δ + 1 to δ − 1 do
        if y + delta ≥ hy or y + delta < 0 or x + j ≥ hx or x + j < 0 then
            continue
        else
            if P[x + j][y + δ] ≥ μ and S[x + j][y + δ] == false then
                x' ← x + j
                y' ← y + δ
                μ ← P[nx][ny]
            end if
        end if
    end for
    for j ← −1 ∗ δ + 1 to δ − 1 do
        if y − δ ≥ hy or y − delta < 0 or x + j ≥ hx or x + j < 0 then
            continue;
        else
            if P[x + j][y − δ] ≥ μ and S[x + j][y − δ] == false then
                x' ← x + j
                y' ← y − δ
                μ ← P[nx][ny]
            end if
        end if
    end for
end for
if x' ≠ −1 and y' ≠ −1 then
    return;
else
    Randomly select location between α-level neighborhood
end if
```

Two parameters are considered in the observation model, namely: *i*) probability of false positive, and *ii*) probability of false negative.[1] For a given cell ς, denote these two parameters as ξ_ς and β_ς, respectively. Let d^ς be the detection measurement of cell ς. A positive target detection event occurs when $d^\varsigma = 1$, and a negative target detection event occurs when $d^\varsigma = 0$. Further let γ be the target cell, which is assumed be an avalanche point. Then, the following conditions can be derived from Chung's error model [33]

$$\begin{aligned}\Pr(d^\varsigma = 1|\varsigma = \gamma) &= 1 - \beta_\varsigma,\\ \Pr(d^\varsigma = 0|\varsigma = \gamma) &= \beta_\varsigma,\\ \Pr(d^\varsigma = 0|\varsigma \neq \gamma) &= 1 - \xi_\varsigma,\\ \Pr(d^\varsigma = 1|\varsigma \neq \gamma) &= \xi_\varsigma.\end{aligned}$$

When the object is positively detected at cell ς, we consider it as the end of the searching operation and marks the start of the rescue operation. Otherwise, the *RBE* updates the probability of target presence at cell ς based on the encountered positive or negative detection events as outlined in [36], i.e.,

$$P'_\varsigma = \begin{cases} \dfrac{(1-\beta_\varsigma)P_\varsigma}{(1-\beta_\varsigma)P_\varsigma + \xi_\varsigma(1-P_\varsigma)}, & \mathit{if}\ d^\varsigma = 1\\ \dfrac{\beta_\varsigma P_\varsigma}{\beta_\varsigma P_\varsigma + (1-\xi_\varsigma)(1-P_\varsigma)}, & \mathit{if}\ d^\varsigma = 0 \end{cases} \tag{1}$$

where P'_ς is the newly calculated probability value of target presence at cell ς and P_ς is the previous value. This calculation is then followed by normalizing the posterior distribution using

$$\bar{P_\varsigma} = \frac{P'_\varsigma}{\sum_{i=1}^{N} P_i} \tag{2}$$

where N is the number of cells in the avalanche area and $\sum_{i=1}^{N} P_i \leq 1$. From each cell, this posterior probability value is then shared with the other teams so that they can update their *PDM* accordingly.

B. SEARCHING APPROACHES

Recall that in any *PST*-based technique, every team maintains a *PDM*. Based on the updating mechanism of the *PDM*, three variants of the technique can be proposed, namely: i) *No PDM Update (NPU)*, ii) *Local PDM Update (LPU)*, and iii) *Global PDM Update (GPU)*. Among these three variants, *GPU* is the only collaborative approach.

1) NO PDM UPDATE (NPU)

In this approach, the *PDM* is never updated and hence, identical *PDM* is invoked every time during the next cell selection process. Since the *PDM* is memoryless, it is highly probable that the same cell will be visited multiple times. In terms of implementation, *NPU* is the simplest among the three variants despite the intuitive prediction that this variant can take the longest duration to detect a target. The *AGCWN* is not required for this approach since there is no information sharing among the rescue teams.

[1] A false positive is a positive result for a test when it should be a negative result. A false negative is a negative result for a test when it should be a positive result.

2) LOCAL PDM UPDATE (LPU)

In this method, the *PDM* is updated locally within a team (intra-team) and the updated information is never shared with the other teams. The method accumulates the previous visits information to prevent visiting the same cell before search completion per iteration. After visiting a cell, the probability of that cell is revised using the *RBE* as discussed in Section IV-A. Since *LPU* utilizes the local memory for selecting the next cell, it requires a lower discovery time than *NPU*. Herein the *AGCWN* is minimally required as it is solely used for enabling limited intra-team communications.

3) GLOBAL PDM UPDATE (GPU)

In contrast to the former two variants, the *GPU* method supports collaboration and cooperation to speed up the *Collab-SAR* activities. In this case, the *AGCWN* is mandatory to enable the communication within the team (i.e., intra-team communication) as well as among the teams (i.e., inter-team communication). As the name suggests, the *PDM* is updated globally. After visiting a cell, the probability of that cell is revised similar to the *LPU* approach. In contrast to *LPU*, the revised probability of the current cell is then shared to the other teams so that they can update their *PDM* accordingly and a consistent global map of the rescue region can be maintained. The previous visits information is also accumulated and utilized in the next cell selection to reduce the probability of searching overlap. As the *PDM* is updated globally and global memory is utilized in the next cell selection, the time taken for target discovery is expected to be the shortest among all the three variants.

V. PERFORMANCE EVALUATION

In this section we analyze the performance of our proposed *Collab-SAR* that exploits a team-driven *AGCWN* infrastructure. We first evaluate the performance of the proposed search technique in Subsection V-A and endeavor to demonstrate the importance of the collaborative effort to speed up the rescue mission. We then demonstrate the effectiveness of the proposed *AGCWN* infrastructure by means of numerical simulations in Subsection V-B,

A. EVALUATION OF ENST

Herein we evaluate the performance of the proposed searching technique (i.e., *ENST*) by comparing it with the other two standard techniques, namely *Random Search Technique (RST)* and *Probabilistic Search Technique (PST)*. For the sake of completeness, we provide a brief discussion on *RST* and *PST* as follows.

1) **Random Search Technique (RST):** The main principle of RST is to select the next cell randomly within 1-level neighborhood. This technique does not require any *PDM* and is considered to be the simplest among all the techniques discussed in this paper. Similarly to *ENST*, RST can be also extended into three variants, namely: *i*) *No Memory (NM)*, *ii*) *Local Memory (LM)*, and *iii*) *Global Memory (GM)*. The *NM* variant does not utilize the knowledge of previously visited cells and hence, a single cell can be visited multiple times. The *LM* variant accumulates self-visited cell information and utilizes it to select the next cell. The *GM* variant is a collaborative approach, which accumulates cell visiting information of all the teams. It utilizes this global knowledge to select the next cell. When all the cells within 1-level neighborhood are visited, then a random cell is chosen. When all the cells of the area are visited and the target has not been discovered, the teams repeat the search activities from the beginning.
2) **Probabilistic Search Technique (PST):** Similarly to the *ENST*, the *PST* utilizes a probabilistic approach for the next cell selection. The difference with *ENST* lies on the fact that herein the next cell is chosen within 1-level neighborhood (instead of α-level neighborhood) of the current cell. When all the cells within 1-level neighborhood have already been visited, the searching technique then selects the next cell randomly from the 1-level neighborhood.

In order to compare the *ENST* with the *RST* and *PST*, an extensive simulation campaign is performed by taking into account near-realistic parameters and near-realistic scenarios. We describe our simulation setup as follows.

1) SYSTEM MODEL

As a proof-of-concept we consider a Euclidean 2-D area of 10000 m $\times$ 10000 m, which is equally divided into a fixed number of cells of size 100 m $\times$ 100 mt. We consider variation in the number of teams, ranging from 1 to 10. At a certain time, one team can only visit a single cell and no cell can be visited by more than one team concurrently. More specific details of the system modeling used in our simulation are described in the following.

A. **Generating PDM:** For any *PST*-based schemes, a *PDM* is mandatory. In order to emulate realistic scenarios, the corresponding *PDM* has to meet a number of requirements. Firstly, the avalanche probability values of all the cells must not be exactly identical. Secondly, a certain degree of relationship in terms of probability values must be maintained between the adjacent cells and there should not be any drastic difference for a continuity reason. Figure 3 shows a near-realistic distribution of the avalanche probabilities in various grid cells, which may represent situation in Alpine environment. As observed from the figure, certain places have higher avalanche probabilities than the others.
B. **Finding Avalanche Point:** One of the primary objectives of the *Collab-SAR* activities is to discover the victims within a short period of time. For the sake of simplicity, consider the case where all the victims are located in a single cell, referred to as *Avalanche Point (AP)*. Again, the likelihood of *AP* is higher in cells with higher avalanche probability values. In order to provide randomization of an *AP* location in the *PDM*,

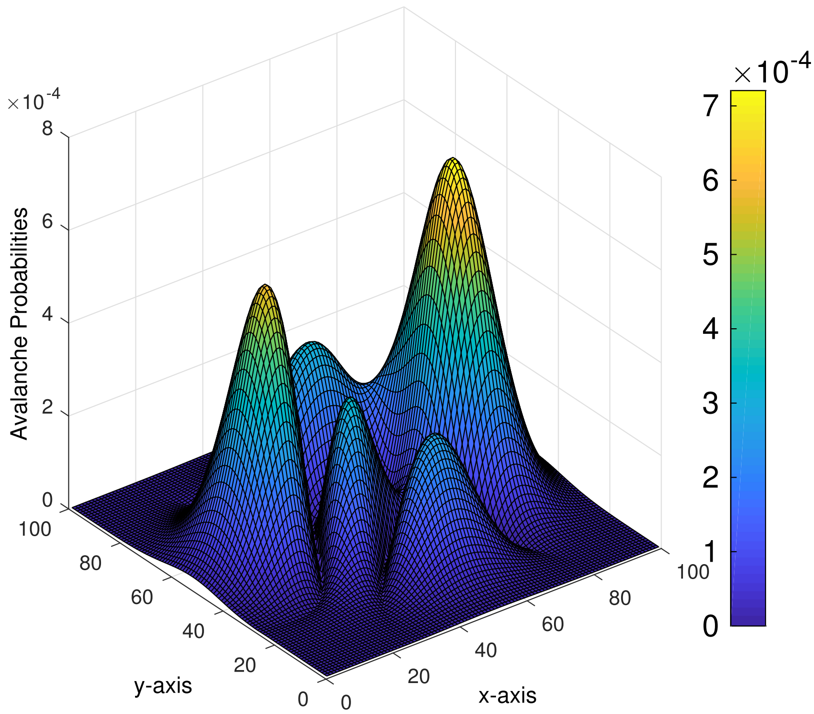


FIGURE 3. Avalanche probabilities of various grid cells.

we utilize a random variable ϱ that takes value in $[0, \mu]$ where μ is the highest value in the *PDM*. (The specific generating function of ϱ is given in Point C. below.) After drawing the value of ϱ, an *AP* must be selected in such a way that the avalanche probability of that cell must be equal or approximately equal (within a tolerable range of $\pm 10^{-6}$) to the value of ϱ. The ''approximately equal'' option is given to facilitate those cases where there is no exact match between the avalanche probability and the value of ϱ. In order to avoid selection of the same cell following a sequential search from a given order, a randomization approach can be employed in which x- and y-coordinates are drawn randomly according to a uniform distribution. Afterwards, the avalanche probability of the newly selected cell is compared to the value of ϱ. This procedure repeats until we find a cell with avalanche probability being equal or approximately equal to the value of ϱ.

C. **Random Number Generator:** As previously mentioned, the random variable $\varrho \in [0, \mu]$ plays an important role in finding an *AP*. In a realistic scenario, the likelihood of occurring avalanche is higher in higher probability cells. Therefore, in our simulation, it is desirable for ϱ to have tendency towards μ where μ is the highest value in the *PDM*. In order to achieve this purpose, we generate ϱ according to

$$\varrho = \frac{(x - 0.5) \times \mu}{0.4959} \tag{3}$$

where x is obtained from a modified *Sigmoid Function*

$$x = \frac{1}{1 + e^{-5.5 \times \vartheta}} \tag{4}$$

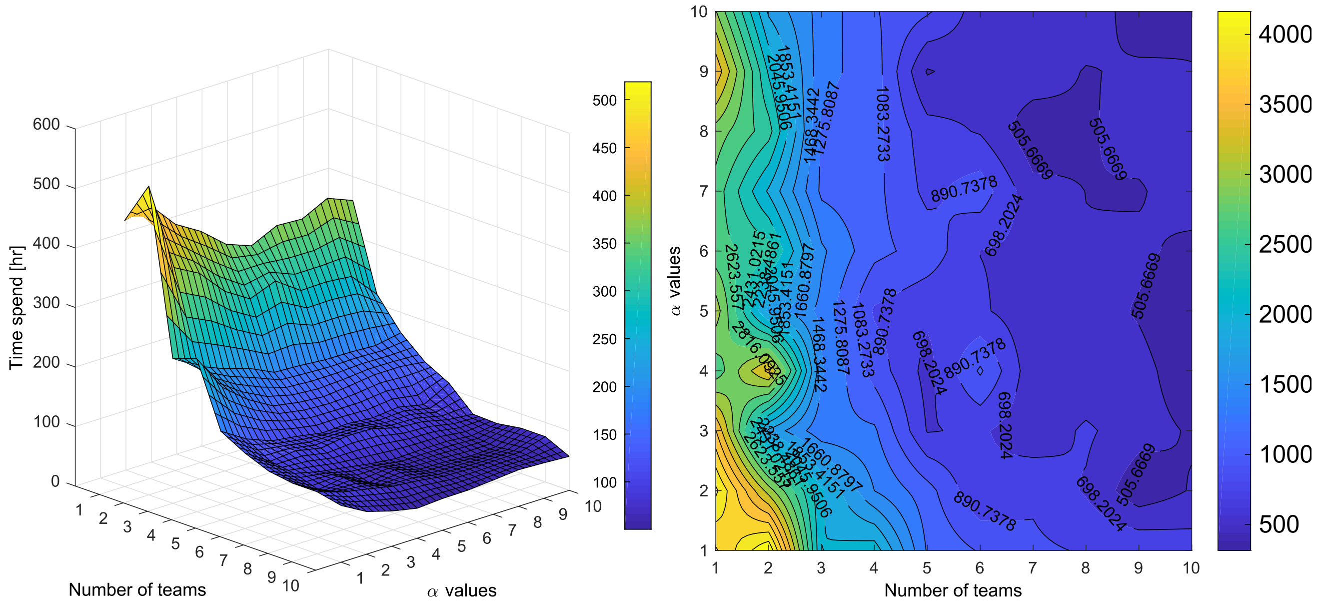
with ϑ being a uniform random variable, taking value in the interval of $[0, 1)$.

2) FINDING OPTIMUM α VALUES

The performance of the *ENST* largely depends on the ability to find the optimum α value. Hence, an extensive simulation campaign has been performed by varying the number of teams involved in the rescue mission and by varying α values. Among the three variants of *ENST*, we highlight the *GPU* method because of the collaborative characteristics. We utilize two metrics to plot the performance, namely the *Time Spend [hr]* and *Average Number of Visited Cells*, which are depicted in Figures 4a and 4b, respectively. Tthe time spend is calculated as

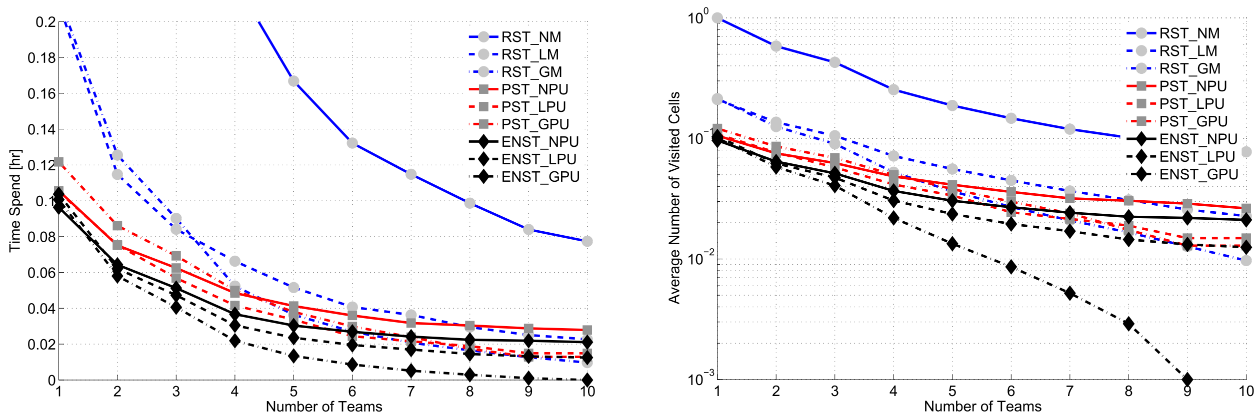
$$\tau = \tau_c + \tau_p + \tau_t. \tag{5}$$

Herein τ_c denotes the cell search time by the intra-team vehicle, which is given by $\tau_c = \sigma_c / \vartheta_V$ where σ_c is the area of the cell and ϑ_V is the average speed of the vehicle. The parameter τ_p is the preparation time—which is considered constant in our simulation—for packing everything before moving to the next cell. The variable τ_t denotes the traveling time from the current cell to the next cell, which depends on the distance between the two cells and the speed of movement from the current cell to the next cell ϑ_C. In our simulation, we set $\vartheta_V = 10$ m/s, $\tau_p = 180$ s and $\vartheta_C = 1.5$ m/s.



(a) (b)

FIGURE 4. **Finding optimum alpha values for various number of teams. (a) Optimum α values for various number of teams in terms of time spent. (b) Optimum α values for various number of teams in terms of cells visited.**



(a) (b)

FIGURE 5. **Finding optimum alpha values for various number of teams. (a) Optimum α values for various number of teams in terms of time spent. (b) Optimum α values for various number of teams in terms of cells visited.**

Figures 4a and 4b show the time spend and number of cell visits for various α values and the number of teams, respectively. If a more number of cells are visited to discover an *AP*, it implies that we incur a longer time to complete the search, and vice-versa. A general observation from both figures is that with increasing number of nodes (i.e., the number of rescue teams), a lower number of cells are visited and hence, a lower search time is required to discover the *AP*. However, a similar trend does not always hold for the α values. The optimum α values lie in between a range. For the case of a single team, the optimum value can be found when $\alpha = 6$. For the case of 10 teams, we find the optimum value is given by $\alpha = 4$. Table 2 summarizes all the optimum α values for different numbers of teams, which will be used for performance comparison in the following Subsubsection.

TABLE 2. **Optimum α values versus the number of teams.**

	Number of Teams									
	1	2	3	4	5	6	7	8	9	10
α	6	10	9	6	9	10	9	8	7	4

3) RESULTS AND DISCUSSIONS

Figures 5a and 5b depict the time that the various teams have spent and the number of cells that various teams have visited before discovering the *AP*. As observed from both figures, the collaborative approach (i.e., the *GPU* variant) outperforms the other variants since it updates the *PDM* globally and utilizes global cell visiting knowledge during the next cell selection. On the other hand, *NPU* has the poorest performance among the three variants due to the absence of *PDM* and cell visiting knowledge for the next cell selection. Even *LPU* performs better than *NPU* due to utilizing local knowledge and updating the *PDM* locally. The results evidently demonstrate the importance of collaborative rescue operations over non-collaborative operations.

Among the three techniques, the *RST* demonstrates the most inferior performance. A key reason is that the next cell is chosen randomly without considering any probability of target presence or avalanche occurrence. Among the three variants of the *RST*, *NM* spends the longest average time to discover *AP*. The same trend can also be observed for the number of visited cells. The *PST* performs better than the *RST* since it selects the next cell based on probabilistic values that are updated locally. The *ENST* outperforms both of its competitors in terms of both the time spent and average number of cell visits. Among the three variants of the *ENST*, *NPU* has the worst performance due to its non-updating nature of the PDM. Conversely, due to the updating process of the *PDM* from time to time either locally or globally by *LPU* and *GPU*, respectively, they demonstrate superior performance over *NPU*. Between the two variants, *GPU* outperforms *LPU* since it updates its *PDM* globally and also utilizes the global cell visiting knowledge. This all shows that our proposed collaborative search technique, which affirms the use of *ENST-GPU* variant, is promising to improve the speed and efficiency of a search and rescue mission.

B. EVALUATION OF AGCWN

In order to analyze the performance of the proposed network infrastructure, we carry out simulation-based experiments in *OPNET* by considering a *WiMAX* module as a standard of choice for the AGCWN. The simulation scenarios and evaluation are discussed below.

1) SIMULATION SCENARIOS

A set of actors involved in the rescue actions, namely *HR*, *SRU*, *LRU-FW*, and *LRU-RW* are considered in this simulation. The overall number of actors are varied from 10 to 100. In terms of data traffic generated in the network, we consider three different classes of *QoS*, namely Gold, Silver, and Bronze, which correspond to the required data rate of 5–1 Mbps, 1–0.5 Mbps and 0.5–0.25 Mbps, respectively, for a fixed channel bandwidth. The latency requirement is set to 30 ms and the speeds of different actors vary, i.e., the speeds for *HR*, *SRU*, *LRU-FW*, and *LRU-RW* are given by 1.5 m/s, 10 m/s, 30 m/s, and 30 m/s, respectively. In order to reduce the design complexity, we consider a static *UGV*[2] with a coverage area of 1 km. This is an implication of the fact that when reaching an arbitrary targeted place for searching the victims, the *UGV* will be first parked. The HR will then get off the *UGV* and start searching with the help of network components.

In the simulation setup, it is necessary to select appropriate mobility and path-loss models that are representative for the AGCWN in Alpine environment. In terms of mobility, we can identify different levels of nodes' mobility based on the characteristics of the network components in Section II-A. For nodes with limited mobility such as *GRs* and *HRs*, a *Random Walk Mobility (RWM)* model [37] is adopted due to its suitability in capturing movement with minimum speed variation. On the other hand, for nodes with medium-level of mobility dynamics such as *SURs* and high-level of mobility dynamics such as *LUR-FW* and *LUR-RW*, we employ a *Random Way-Point Mobility (RWM)* model [38] that allows tuning with variable speeds.

The *Erceg* fading model [39] is adopted to represent the Alpine path-loss, which is the dominant link characteristics in our AGCWN, due to similar hilly characteristics. Speficially, the overall *Erceg* path-loss P_L in dB between two communicating nodes at distance x can be expressed as

$$P_L(dB) = \alpha + 10\gamma \log_{10}\left(\frac{x_0}{x}\right) + s_f \tag{6}$$

where α, x_0, γ and s_f denotes the intercept, reference distance (set to 100 m in our simulation), path loss exponent and shadow fading, respectively. The intercept parameter α is of a fixed value and given by

$$\alpha = 20 \log_{10}\left(\frac{4\pi x_0}{\lambda}\right) \tag{7}$$

where λ corresponds to the wavelength of the propagating wireless signal. The path-loss exponent γ in equation (6) is specified by

$$\gamma = (A - BH_B + C/H_B) + L\sigma_\gamma \tag{8}$$

where A, B and C are pre-determined terrain-dependent constants obtained from empirical data [39], $H_B \in [10, 80]$ (in meters) denotes the height of base station antenna, L corresponds to a zero-mean unit-variance Gaussian random variable $\mathcal{N}(0, 1)$, and $\sigma_\gamma > 0$ governs the standard deviation of γ. The shadow fading term s_f in the model (6) is a product of two random variables K and σ where K follows zero-mean unit-variance Gaussian distribution $\mathcal{N}(0, 1)$ and σ follows mean-$\bar{\sigma}$ and variance-σ_σ^2 Gaussian distribution $\mathcal{N}(\bar{\sigma}, \sigma_\sigma^2)$. The parameters $\bar{\sigma}$ and σ_σ are both terrain-dependent constants and obtained from empirical measurement.

Typical values of all these model parameters are tabulated in Table 3 for three different categories of terrain, namely:

- Category TC_1–Hilly/Moderate-to-Heavy-Tree-Density,
- Category TC_2–Hilly/Light-Tree-Density or Flat/ Moderate-to-Heavy-Tree-Density,
- Category TC_3–Light/Flat-Tree-Density.

2) RESULTS AND DISCUSSIONS

We evaluate the performance of our proposed *AGCWN* using the following two metrics. The first metric is the *normalized throughput (NT)*, which is defined by the total data traffic per unit (in packets/s) successfully delivered to the *WiMAX* MAC layer at the receiver and subsequently forwarded to the higher layer. The second metric is the *normalized communication*

[2]The *UGV* will remain static while the actors are communicating.

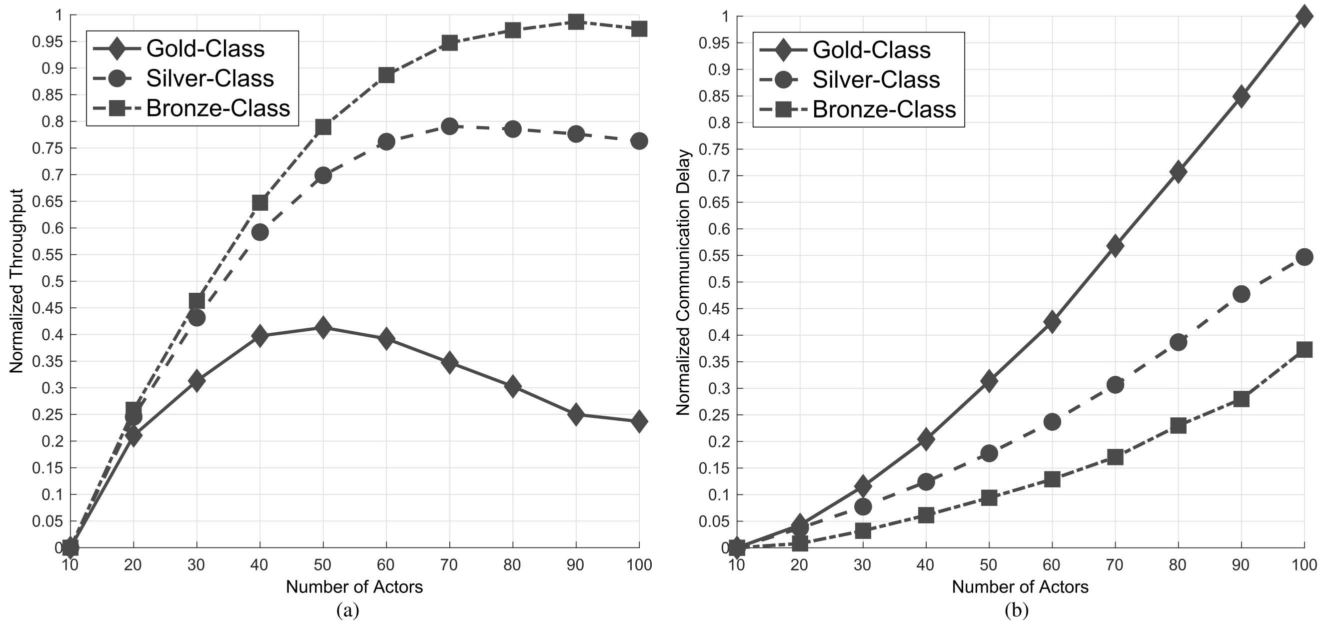


FIGURE 6. Evaluation results of the proposed *AGCWN*. (a) Number of actors vs normalized throughput. (b) Number of actors vs communication delay.

TABLE 3. Numerical values of Erceg model parameters [39].

Model Parameter	Terrain Category		
	TC_1	TC_2	TC_3
A	4.6	4.0	3.6
B (m^{-1})	0.0075	0.0065	0.0050
C (m)	12.6	17.1	20.0
σ_γ	0.57	0.75	0.59
$\bar{\sigma}$	10.6	9.6	8.2
σ_σ	2.3	3.0	1.6

delay (NCD), which corresponds to the time spent by a packet to reach its intended destination.[3]

Figure 6a depicts the *NT* against the number of actors in the network with different QoS classes, namely Gold, Silver and Bronze. From the figure, we can see that initially the throughput increases with the increasing number of actors for all the QoS classes until reaching a saturation point. Beyond this saturation point, the throughput declines with the increasing number of actors. Since the *Gold class* supports the highest data rate, the saturation point of the *NT* occurs very early, i.e., just after 50 actors. On the other hand, for the *Silver class*, the throughput starts declining just after 70 actors. For the *Bronze class*, the decline of the *NT* occurs after 90 actors due to a lower support of the data rate.

Figure 6b plots the results of the *NCD* against the number of actors for three QoS classes, i.e., Gold, Silver and Bronze. We observe from the figure that the *NCD* monotonously increases with the increasing number of actors. This is so because of the channel partitioning effect of the *WiMAX* MAC layer, in which the more number of actors are active, the more channel divisions occur. In such a case, an actor may get a lower transmission time, which implies that a lower rate data transmission experiences a lower delay. In this particular context, the *Bronze class* outperforms its counterparts due to the lowest data rate demand.

[3]Remark that the value of NCD is computed by accounting only for the data packets that are successfully received.

VI. CONCLUSIONS

We have presented a *Collab-SAR* technique for human rescuing missions in hostile Alpine environment. More specifically, we have proposed the *AGCWN* infrastructure with the objective of enabling wireless communications among the rescue agents —as envisioned in the SHERPA project—by taking into account the main communication requirements, namely high throughput and long range coverage. In order to develop a fit-for-purpose infrastructure for the *AGCWN* in Alpine environment, we have performed a comparative study among several existing wireless technologies and selected the most suitable one. As an integral part of *Collab-SAR*, we have proposed the *ENST* as a variant of the prominent *PST*, which serves as a collaborative search technique to speed up the searching operation. The *ENST* has been developed by utilizing intra- and inter-team information exchange enabled by the *AGCWN* infrastructure. The simulation results have demonstrated the promise of the proposed *Collab-SAR* components to assist in speedily locating avalanche victims and thereby providing rapid rescue actions within Alpine environment.

REFERENCES

[1] *Alpine Tourism*. Accessed: Feb. 27, 2018. [Online]. Available: http://wwf.panda.org/what_we_do/where_we_work/alps/problems/tourism/
[2] *Swiss Air Rescue*. Accessed: Feb. 27, 2018. [Online]. Available: http://www.rega.ch/en/home.aspx
[3] F. Techel *et al.*, "Avalanche fatalities in the European Alps: long-term trends and statistics," *Geographica Helvetica*, vol. 71, pp. 147–159, Jun. 2016.
[4] SHERPA Project. (Nov. 21, 2017). *Smart Collaboration Between Humans Ground-aErial Robots for Improving Rescuing Activities Alpine Environments (SHERPA)*. [Online]. Available: http://www.sherpa-project.eu/sherpa/

[5] L. Marconi *et al.*, "The SHERPA project: Smart collaboration between humans and ground-aerial robots for improving rescuing activities in alpine environments," in *Proc. IEEE Int. Symp. Saf., Secur., Rescue Robot. (SSRR)*, Nov. 2012, pp. 5–8.
[6] Z. Sheng, C. Mahapatra, C. Zhu, and V. C. M. Leung, "Recent advances in industrial wireless sensor networks toward efficient management in IoT," *IEEE Access*, vol. 2, pp. 622–637, 2015.
[7] D. Zhang, L. T. Yang, M. Chen, S. Zhao, M. Guo, and Y. Zhang, "Real-time locating systems using active RFID for Internet of Things," *IEEE Syst. J.*, vol. 10, no. 3, pp. 1226–1235, Sep. 2016.
[8] Z. Zhou, M. Dong, K. Ota, G. Wang, and L. T. Yang, "Energy-efficient resource allocation for D2D communications underlaying cloud-RAN-based LTE-A networks," *IEEE Internet Things J.*, vol. 3, no. 3, pp. 428–438, Jun. 2016.
[9] X. Luo, D. Zhang, L. Yang, J. Liu, X. Chang, and H. Ning, "A kernel machine-based secure data sensing and fusion scheme in wireless sensor networks for the cyber-physical systems," *Future Gener. Comput. Syst.*, vol. 61, pp. 85–96, Aug. 2016.
[10] S. Hashish, "Dynamic concentric rings infrastructure for efficient communications in wireless sensor networks," *IEEE Access*, vol. 4, pp. 3605–3616, 2016.
[11] S. Azad, M. A. Rahman, A. T. Asyhari, and A.-S. K. Pathan, "Crowd associated network: Exploiting over a smart garbage management system," *IEEE Commun. Mag.*, vol. 55, no. 7, pp. 186–192, Jul. 2017.
[12] X. Lai, W. Zou, D. Xie, X. Li, and L. Fan, "DF relaying networks with randomly distributed interferers," *IEEE Access*, vol. 5, pp. 18909–18917, 2017.
[13] M. Z. A. Bhuiyan, G. Wang, J. Wu, J. Cao, X. Liu, and T. Wang, "Dependable structural health monitoring using wireless sensor networks," *IEEE Trans. Depend. Sec. Comput.*, vol. 14, no. 4, pp. 363–376, Jul./Aug. 2017.
[14] X. Xing, D. Xie, and G. Wang, "Energy-balanced data gathering and aggregating in WSNs: A compressed sensing scheme," *Int. J. Distrib. Sensor Netw.*, vol. 11, no. 10, p. 585191, 2015.
[15] L. Fan, X. Lei, N. Yang, T. Q. Duong, and G. K. Karagiannidis, "Secrecy cooperative networks with outdated relay selection over correlated fading channels," *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 7599–7603, Aug. 2017.
[16] W. Zhao and J. Xie, "ReLoAD: Resilient location area design for Internet-based infrastructure wireless mesh networks," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, Kathmandu, Nepal, Dec. 2011, pp. 1–5.
[17] R. E. Castellanos and P. Millán, "Design of a wireless communications network for advanced metering infrastructure in a utility in Colombia," in *Proc. IEEE Colombian Commun. Conf. (COLCOM)*, Cali, Columbia, May 2012, pp. 1–6.
[18] M. A. Rahman, "Reliability analysis of ZigBee based intra-vehicle wireless sensor networks," in *Proc. Int. Workshop Commun. Technol. Vehicles*, 2014, pp. 103–112.
[19] A. White, *A Collaboration Network for Unmanned Aerial Vehicle Operation, Research and Education*. Fort Belvoir, VA, USA: Defense Technical Information Center, 2005.
[20] G. Tuna, T. V. Mumcu, K. Gulez, V. C. Gungor, and H. Erturk, "Unmanned aerial vehicle-aided wireless sensor network deployment system for post-disaster monitoring," in *Proc. Int. Conf. Intell. Comput.*, vol. 304. Huangshan, China: Springer, 2012, pp. 298–305.
[21] S. Morgenthaler, T. Braun, Z. Zhao, T. Staub, and M. Anwander, "UAVNet: A mobile wireless mesh network using unmanned aerial vehicles," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2012, pp. 1603–1608.
[22] Y. Saleem, M. H. Rehmani, and S. Zeadally, "Integration of cognitive radio technology with unmanned aerial vehicles: Issues, opportunities, and future research challenges," *J. Netw. Comput. Appl.*, vol. 50, pp. 15–31, Apr. 2015.
[23] J. Valente, D. Sanz, A. Barrientos, J. D. Cerro, Á. Ribeiro, and C. Rossi, "An air-ground wireless sensor network for crop monitoring," *Sensors*, vol. 11, no. 6, pp. 6088–6108, 2011.
[24] L. Chaimowicz *et al.*, "Deploying air-ground multi-robot teams in urban environments," in *Proc. Int. Workshop Multi-Robot Syst.*, 2005, pp. 223–234.
[25] M. Dille, B. Grocholsky, S. T. Nuske, M. Moseley, and S. Singh, "Air-ground collaborative surveillance with human-portable hardware," in *Proc. AUVSI Unmanned Syst. North Amer.*, 2011, pp. 1–20.
[26] M. A. Rahman, "Enabling drone communications with WiMAX technology," in *Proc. IISA*, Chania, Greece, Jul. 2014, pp. 323–328.
[27] M. A. Rahman, "SHERPA: An air-ground wireless network for communicating human and robots to improve the rescuing activities in alpine environments," in *Proc. 8th Int. Conf. Ad-Hoc Netw. Wireless*, 2014, pp. 290–302.
[28] M. H. De Groot, *Optimal Statistical Décisions*. Hoboken, NJ, USA: Wiley, 2004.
[29] T. Dougherty, "The loss of the USS scorpion: Myths, legends, & reality," vol. 8, no. 10, pp. 1–24, Oct. 2012, PERISCOPE, Los Angeles, USA, Tech. Rep.
[30] N. S. Center, "What's happening? The loss of air France flight 447," *Syst. Failure Case Study, ISASI Forum*, vol. 6, no. 7, pp. 1–32, Aug. 2013.
[31] A. Whitley. (Sep. 21, 2016). *MH370 Hunters Narrow Down Most Likely Site Wreckage*. [Online]. Available: http://www.bloomberg.com/news/articles/2015-12-02/mh370-hunters-say-new-analysis-reaffirms-most-likely-wreck-site
[32] A. J. Haug, *Bayesian Estimation and Tracking: A Practical Guide*. Hoboken, NJ, USA: Wiley, 2012.
[33] T. H. Chung and J. W. Burdick, "A decision-making framework for control strategies in probabilistic search," in *Proc. IEEE Int. Conf. Robot. Automat.*, Apr. 2007, pp. 4386–4393.
[34] A. S. Cacciapuoti, M. Caleffi, L. Paura, and R. Savoia, "Decision maker approaches for cooperative spectrum sensing: Participate or not participate in sensing?" *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2445–2457, May 2013.
[35] A. S. Cacciapuoti, I. F. Akyildiz, and L. Paura, "Optimal primary-user mobility aware spectrum sensing design for cognitive radio networks," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 11, pp. 2161–2172, Nov. 2013.
[36] A. Symington, S. Waharte, S. Julier, and N. Trigoni, "Probabilistic target detection by camera-equipped UAVs," in *Proc. IEEE Int. Conf. Robot. Automat.*, Anchorage, AK, USA, May 2010, pp. 4076–4081.
[37] T. Camp, J. Boleng, and V. Davies, "A survey of mobility models for ad hoc network research," *Wireless Commun. Mobile Comput.*, vol. 2, no. 5, pp. 483–502, Sep. 2002.
[38] C. Bettstetter, H. Hartenstein, and X. Pérez-Costa, "Stochastic properties of the random waypoint mobility model," *Wireless Netw.*, vol. 10, no. 5, pp. 555–567, 2004.
[39] V. Erceg *et al.*, "An empirically based path loss model for wireless channels in suburban environments," *IEEE J. Sel. Areas Commun.*, vol. 17, no. 7, pp. 1205–1211, Jul. 1999.
[40] M. Z. A. Bhuiyan, J. Wu, G. Wang, and J. Cao, "Sensing and decision making in cyber-physical systems: The case of structural event monitoring," *IEEE Trans. Ind. Informat.*, vol. 12, no. 6, pp. 2103–2114, Dec. 2016.
[41] M. Z. A. Bhuiyan, G. Wang, J. Cao, and J. Wu, "Deploying wireless sensor networks with fault-tolerance for structural health monitoring," *IEEE Trans. Comput.*, vol. 64, no. 2, pp. 382–395, Feb. 2015.
[42] M. Z. A. Bhuiyan, J. Wu, G. Wang, T. Wang, and M. Hassan, "e-Sampling: Event-sensitive autonomous adaptive sensing and low-cost monitoring in networked sensing systems," *ACM Trans. Auton. Adapt. Syst.*, vol. 12, no. 1, 2017, Art. no. 1.
[43] X. Chen, X. Huang, J. Li, J. Ma, W. Lou, and D. S. Wong, "New algorithms for secure outsourcing of large-scale systems of linear equations," *IEEE Trans. Inf. Forensics Security*, vol. 10, no. 1, pp. 69–78, Jan. 2015.
[44] X. Zhang, Y.-A. Tan, C. Liang, Y. Li, and J. Li, "A covert channel over VoLTE via adjusting silence periods," *IEEE Access*, vol. 6, pp. 9292–9302, 2018.

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