Spatial sampling methods for improved communication for wireless relay robots

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Abstract — Having reliable wireless communication in a network of mobile robots is an ongoing challenge, especially when the mobile robots are given tasks in hostile or harmful environments such as radiation environments in scientific facilities, tunnels with large metallic components and complicated geometries as found at CERN. In this paper, we propose a decentralised method for improving the wireless network throughput by optimizing the wireless relay robot position to receive the best wireless signal strength using implicit spatial diversity concepts and gradient-search algorithms. We experimentally demonstrate the effectiveness of the proposed solutions with a KUKA Youbot omni-directional mobile robot. The performance of the algorithms is compared under various scenarios in an underground scientific facility at CERN.

Keywords: *Networked mobile robots, multi-hop wireless communication, gradient search, spatial diversity*

I. Introduction

CERN, the European Organization for Nuclear Research, has around 50 km of underground scientific facilities, where mobile robots could help in the operation of the particle accelerator facilities, e.g. in conducting remote inspections and radiation surveys in different areas [1]–[3].

The main challenges to be considered here are not only that the robot should be able to go over long distances and operate for relatively long periods, but also the underground tunnel environment, the possible presence of electromagnetic fields, ionizing radiation, and the fact that the robots shall in no way disrupt the operation of the accelerators.

In this kind of hostile environments, wired communications have not proved reliable, with fiber-optic cables susceptible to tangling, breakage, and being run over by the robot [4]. On the other hand, wireless communications have also found to be unreliable [5], [6]. However, wireless communication offers solutions to some of the fundamental challenges of all tethered communication systems with benefits such as low maintenance, high robustness against failures stemming from physical damage, less manpower needed for managing the tethers and ease of mobility.

Wireless communication in underground mine tunnels had been investigated in [6] and the authors highlight the necessity of placing repeater nodes as the wireless network did not perform well under non-line of sight (NLOS) condition.

Mobile ad-hoc networks (MANETs) using a team of autonomous mobile robots have been widely studied and demonstrated [7], [8]. Particularly in NLOS environments, mobile robot platoons can be used as wireless relays to form a wireless network from the operator base station to the main robot performing search or rescue missions. The wireless system should also be able to tolerate interferences and multipath effects [7].

Given the dynamic changes in the wireless signal behaviour arising from movement of objects and changes in the environment, optimising the relay robot's position will optimise the wireless network performance of the main robot performing the assigned tasks such as search, inspection or survey.

Given the hostile environment in which the robot is going to be deployed, it has to be taken into account that several components of the wireless devices may fail or get damaged. This can for instance happen due to radiation effects. Hence, there is also a need for redundancy features in the communication devices in order to avoid communication failures and enable recovery in the event of failure.

The wireless network throughput has a strong correlation with the received signal strength (RSS). The higher the RSS, the higher is the wireless network throughput: an improvement of $1\,\mathrm{dBm}$ in RSS will trigger an improvement of approximately $1\,\mathrm{Mb/s}$ in throughput when the RSS is above -86 dBm [9].

Hence, in an attempt to improve the wireless signal strength, we present a decentralised method for wireless relay robot positioning using a gradient-search algorithm to optimize the wireless signal strength at the relay robot using the spatial diversity concept (receiving radio signals with multiple receivers at different positions) and we also implement redundancy feature in our method. The main objective behind this work is to navigate the mobile robot to a position where the received signal strength is a local maximum or at least above the minimum threshold. This method applies only to the relay robots (used for wireless tethering) and not to the task robot which performs the actual tasks/inspections.

The main contributions in this paper are the following.

1) We propose a methodology for using simultaneous spatial and temporal measurements to find the best signal strength thereby enhancing the throughput and redundancy of the wireless network.
2) We give experimental results of the proposed variants

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with performance metrics such as improvement in signal strength, time taken, distance travelled by the robot.
3) The objective of this research is also to investigate the time-independent methods for RSS measurements (RSS sampled at the same time) used for localisation or motion planning compared to time-dependent methods (RSS sampled at different times).

The work described in this paper is a step towards fully autonomous relay robots that optimise their position in relation to the task robot's position.

A. Related work

Many researchers have attempted to improve the wireless connectivity in a network of mobile robots using various techniques [10]–[16]. The use of relay nodes in tackling serious communication issues are addressed with solutions such as self-configuration, self-healing and wireless tethering that are explained in DARPA Landroids [13] program.

In [10], the authors suggest motion planning techniques in a group of mobile robots to increase the robustness in wireless networking. They propose a global search based method adopting a stochastic model for mobility planning for a group of robots.

In [12], a team of mobile robots including ground and aerial robots used wireless tethering concepts for collectively achieving a task of exploring the environment. The authors follow a decentralised approach with the aerial robots as relay robots and present an antenna diversity method for positioning the relay robot using a gradient search technique, i.e., multiple antennas are connected to a receiver and are used to sample the RSS at all the antennas to obtain the direction of the highest RSS [15]. However, this method is time-dependent and could suffer from temporal fluctuations in RSS.

Research has been done on using radio signal strength (RSS) for localisation of mobile robots and wireless tethering in multi-robot networks [11], [14], [16], [17]. In [14], a data driven probabilistic model is used for RSS based localisation and wireless tethering algorithms.

Radio source seeking techniques are studied using RSS gradient [11] and angle of arrival methods [17]. The use of directional antennas and pattern based search algorithms is presented in [16] for improving the RSS.

Most of the research solutions possess drawbacks such as the use of customised hardware with changes at the physical layer in the network stack of the wireless router (such as wireless transceivers with multiple directional antennas). The dependency on hardware design could be overcome by using algorithms acting in the application layer that can easily be integrated and shared. None of the previous research in RSS based tethering of robots utilised multiple receivers and time-independent methods for improving the RSS.

In our paper, we utilise a concept similar to the concepts used in [15] and [16]. However, instead of using multiple antennas connected to the same receiver, we use multiple receivers as shown in Figure 1. Therefore, we avoid the need to switch between different antennas connected to a same receiver. Instead, our approach is to use RSS gradient information to position the relay robot to obtain a relatively better RSS (local maxima), thereby increasing the communication range and coverage area.

Our method does not require prior knowledge of the environment and is novel as indicated below:

- The algorithms we developed are fully 2-D, in contrast to the greedy algorithms used in [15], [16] which approximate the 2-D physical reality by doing sequential 1-D computations that combine to 2-D. By doing so, we have more opportunity to experiment with, for instance, different finite difference stencils, and can demonstrate that the time dependence of the WIFI field cannot always be neglected.
- We use multiple receivers distributed spatially for measuring the RSS and estimating the RSS gradient at the center of the robot.
- Because we use multiple low-cost transceivers with high receive sensitivity, there exists an advantage of redundancy and fault-tolerance. When the connectivity is lost with one receiver either because of fault in the device or due to environmental influence, other receivers can replace the failed receiver. Furthermore, the history of the RSS at all the receivers can help in navigating the robot towards the region where the connection was available in order to recover the robot from communication failure situations. This redundancy feature could be very useful in a rescue scenario and was also not explored in the literature of relay robots.

II. Methodology

The RSS varies randomly because the signal propagates through a multi-path fading channel (radio signals from the transmitter arriving at the receiver through multiple paths and the signal strength fades with distance travelled). The attenuation in the power of the radio signal is defined as the path loss PL and is caused by many factors such as distance (free space loss) and multi-path propagation effects. In particular, all walls, ceilings, and other objects that affect the propagation of radio waves will directly influence the signal strength and the directions from which radio signals are received. The path loss can be modelled as a log-normal

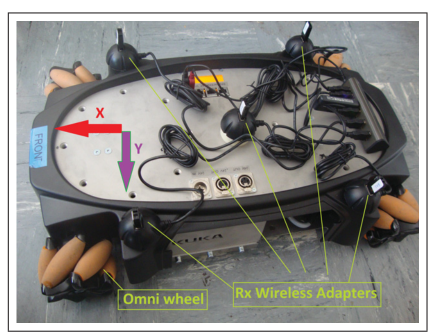


Fig. 1: Youbot mobile robot with multiple wireless receivers

distribution [18]:

$$PL_d = PL_{d_0} + 10 \cdot n \cdot \log(\frac{d}{d_0}) + \mathcal{X}_\sigma \qquad [\text{dBm}] \quad (1)$$

where, PL_d is the path loss at distance d, PL_{d_0} is the path loss at reference distance d_0, n is an environment specific propagation constant, and χ_σ is a Gaussian distribution with zero mean and variance σ_x. n and σ_x together define the environment and χ_σ represents the large scale fading because of shadowing effects [19].

The RSS (or the received power) P_R is equal to the difference in the transmitted power P_T and the path loss PL_d over a distance d,

$$P_R = P_T - PL_d \qquad [\text{dBm}] \quad (2)$$

According to Shannon's capacity theorem [20], in a wireless system, the communication channel capacity C is related to the signal's received power P_R as follows:

$$C = B \cdot log_2(1 + \frac{P_R}{P_N}) \qquad [\text{Mb/s}] \quad (3)$$

where, B is the bandwidth of the channel in Hz and P_N is the power of the noise in the channel. This indicates that the data throughput in the wireless network, which is a measure of the channel capacity C, depends on the RSS.

In a typical wireless network, when the connectivity worsens either because of movement of the receiver and/or the transmitter or change in antenna orientation, the network data rate is adjusted downward to maintain the reliability in the connection. In general, high frequency channels perform better in heavy traffic conditions compared to low frequency channels in the ISM band. In a poorly selected channel, the received signal level is not affected but the noise level will be higher which degrades the link quality. It is assumed in our work that the best channel is already chosen based on the traffic conditions, to avoid adjacent and co-channel interference and hence channel optimisation is assumed to be already done.

We propose a method on improving the RSS with the help of spatial diversity without explicitly implementing antenna diversity (using multiple receivers instead of multiple antennas). Our algorithm is itself not aware of the robot position.

A. Algorithm

To enable the mobile robot move to an optimal position for receiving better wireless signal strength, we make use of a gradient ascent algorithm. Gradient ascent, or the method of steepest ascent, is an iterative optimization algorithm, with steps proportional to the gradient of the optimization function at the current point [21].

With the robot moving on a 2D surface (X, Y) with the current position of the mobile robot as (X^i, Y^i), the RSS values at each receiver k as R_k^i where $k = 1, 2...N$, and $N \leq 5$ as the number of receivers used (based on the arrangements of sensors), the algorithm can be expressed as follows:

The α_x and α_y are pre-defined step size parameters that depend on the spacing of sensors in x and y dimensions ($\alpha_x \propto \Delta_x$, $\alpha_y \propto \Delta_y$). In our algorithm, we do not aim to reach the

Algorithm 1 Wireless signal gradient ascent algorithm

```
Measure the RSS at central receiver R^i_meas = R^i_1
while (R^i_meas < R^i_threshold) do
    Compute the gradient in ∇R^i as ∇⃗R^i = (∇R^i_x, ∇R^i_y)
    X^{i+1} = X^i + α_x · ∇R^i_x
    Y^{i+1} = Y^i + α_y · ∇R^i_y
    Move the robot to position (X^{i+1}, Y^{i+1})
end while
```

global optimum, because within a reasonable range around the robot's local optimum, the wireless communication quality is sufficient. The stop criterion was defined as a threshold RSS level, depending on the experimental set-up (see section III).

Since we use a local, gradient-estimation-based, optimisation algorithm, we avoid circular symmetry issues (uniform radiation around the source) with gradient search algorithms as the radio signals suffers from huge multipath effects in hostile environments because of thick concrete walls in the tunnel and large metallic objects.

B. Approach

We use the concept of spatial diversity by using multiple receivers at the robot. Diversity helps in dealing with the multi path fading effects. In antenna diversity [15] and beam steering/forming techniques [17], multiple antennas are used with one signal receiver to trap the radio signals in one or several antennas at a time forming a beam pattern. However, the difference in our method compared to antenna diversity techniques is that we use multiple receivers to form spatial diversity, therefore minimising signal processing loads at the physical or the data link layers in the network stack (OSI reference model).

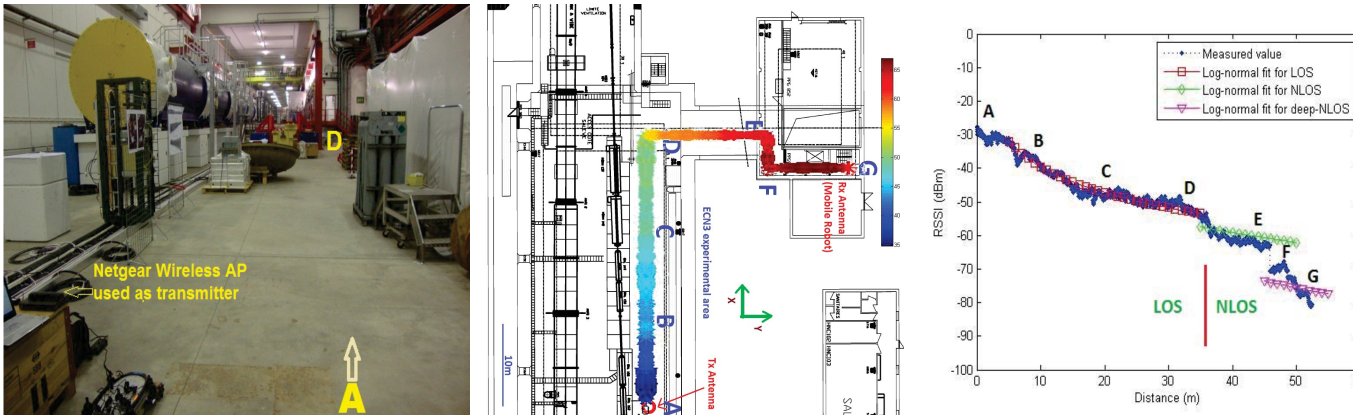
We propose two types of architectures to implement our algorithm 1. The first variant is to use multiple transceivers on the robot and measure the RSS values at different positions at the same time. In the second variant, only one receiver is used and the robot moves locally in a pre-determined structure to measure the RSS values at different positions.

III. Experimental setup

For executing the experiments, we used a KUKA Youbot [22] as the relay robot. Since the Youbot has omni-directional wheels (which permit any combination of longitudinal, transversal and rotational movement of the robot), navigation is efficient given the space restrictions in the underground scientific facility. The control equations for the Youbot located in inertial frame of reference pose (X, Y, Θ), are given as follows:

$$\begin{bmatrix} X_t \\ Y_t \\ \Theta_t \end{bmatrix} = \begin{bmatrix} X_{t-1} \\ Y_{t-1} \\ \Theta_{t-1} \end{bmatrix} + \begin{bmatrix} \pm\vartheta_X & 0 & 0 \\ 0 & \pm\vartheta_Y & 0 \\ 0 & 0 & \pm\omega \end{bmatrix} \begin{bmatrix} \tau_\vartheta \\ \tau_\vartheta \\ \tau_\omega \end{bmatrix}$$

where, ϑ_x, ϑ_y, and ω are the longitudinal, transversal and rotational velocities respectively. τ_ϑ and τ_ω are time constants which determine the displacements $\delta x, \delta y$, and $\delta\theta$ in



(a) View of the ECN3 tunnel (b) ECN3 layout and measured RSS values (c) $RSSI$ with distance along the robot path

Fig. 2: RSS measurements in ECN3 tunnel facility at CERN

$X, Y,$ and Θ directions.

$$\tau_\vartheta = \frac{\sqrt{(\delta X)^2 + (\delta Y)^2}}{\vartheta} \text{ and } \tau_\omega = \frac{\delta\Theta}{\omega}$$

The value of $\vartheta_X = \vartheta_Y = \vartheta$ is fixed at $0.1\,\mathrm{m/s}$ and we did not use the rotational DoF Θ as the Youbot can be controlled independently in each DoF (holonomic platform).

A static wireless transmitter (ProSafe Dual Band Wireless-N Access Point WNDAP350 [23]), only used for control data (not involved in the algorithm) and five compact Wi-Fi receiver stations (Zyxel NWD2105 [24]) are used in the experiments. The transmitter [23] uses the IEEE 802.11n 2.4 GHz standard with a maximum transmit power $P_T = 20\mathrm{dBm}$, and a maximum data-rate of $144.44\,\mathrm{Mb/s}$. The receiver [24] has a receive sensitivity threshold R_S of $64\,\mathrm{dBm}$ at $64\,\mathrm{Mb/s}$ and $-82\mathrm{dBm}$ at $11\,\mathrm{Mb/s}$. The transmitter was fixed at a position $(X, Y) = (0, 0)$ and the receiver stations were mounted at different positions on the Youbot as shown in Figure 1.

The experiments were conducted in a tunnel facility known as ECN3 at CERN, shown in Figures 2a and 2b. Each receiver was set to channel 3 in the 2.4 GHz spectrum and all the receivers have same characteristics. The RSS values were obtained with the RSS indicator ($RSSI$) using the `iwlist scan` command or the `iwconfig` command in Linux which is computationally less expensive than `iwlist`. The Zyxel NWD2105 receiver uses the RALink 2850 wireless driver and the $RSSI$ measurement is equal to the received signal power in dBm, $RSSI = RSS = R$. Each $RSSI$ sample is measured at a 100 Hz sampling rate for 1 s, and then averaged to diminish the statistical temporal fluctuations:

$$\overline{RSSI} = \frac{1}{100} \cdot \sum_{i=1}^{100} RSSI_i$$

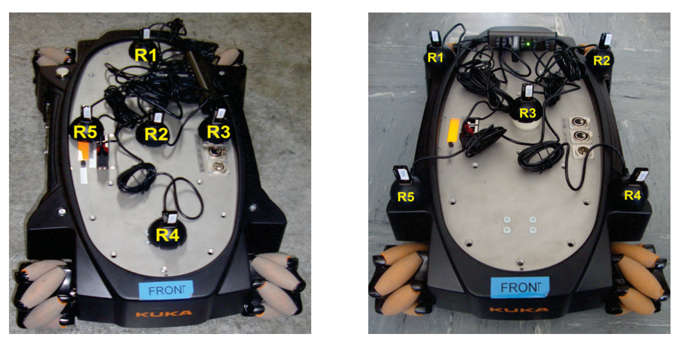
.

In a preliminary experiment [25] to understand the variation in $RSSI$ in an underground tunnel facility, the robot was driven along a path defined by points A to G, as shown in figure 2b, selected to accommodate LOS and NLOS conditions. Figure 2b shows the path taken by the robot and measured RSS values along the robot path. The colour of the RSS values indicated the mean RSS value (μ) among the five receivers and the width indicates the standard deviation (σ). We can observe that the variation (σ) of RSS among the receivers decreases when the robot is moving away from transmitter. The log-normal fits can be obtained for n and σ_x from the equation 1 under LOS and NLOS conditions in the ECN3 tunnel (figure 2c). It can be observed that the $RSSI$ values decay faster in NLOS than in LOS condition.

A. Algorithmical setup

Algorithm 1 was executed using two different approaches.

1) Static stencils (time-independent sampling): using up to five receivers on the Youbot at the same instant for computing 2D RSS gradients.
2) Dynamic stencils (time-dependent sampling): using only the central receiver, the Youbot was made to move dynamically to create a stencil pattern.



(a) Diamond configuration (b) Rectangular configuration

Fig. 3: Wireless receivers configuration on Youbot

The dynamic stencil approach has the disadvantage that changes in the temporal dimension need to be negligible, while the static stencil method necessitates more wireless receivers

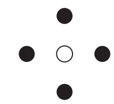
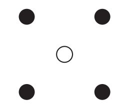
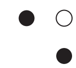
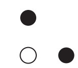
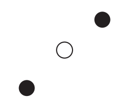
Hardware configuration	Description	Formula	Stencil	Representation
Diamond configuration	Classical 2D five-point stencil, first-order central differences [5_pCL]	$\begin{bmatrix} \frac{R^i_{j+1,k}-R^i_{j-1,k}}{2\Delta_x} \\ \frac{R^i_{j,k+1}-R^i_{j,k-1}}{2\Delta_y} \end{bmatrix}$		5_pCL
Rectangular configuration	Averaged 2D five-point stencil, first-order central differences [5_pC-Static, 5_pD-Dynamic]	$\begin{bmatrix} \frac{1}{2}\left(\frac{R^i_{j+1,k-1}-R^i_{j-1,k-1}}{2\Delta_x}+\frac{R^i_{j+1,k+1}-R^i_{j-1,k+1}}{2\Delta_x}\right) \\ \frac{1}{2}\left(\frac{R^i_{j-1,k+1}-R^i_{j-1,k-1}}{2\Delta_y}+\frac{R^i_{j+1,k+1}-R^i_{j-1,k+1}}{2\Delta_y}\right) \end{bmatrix}$		5_pC, 5_pD
Diamond configuration	2D three-point stencil, first-order backward differences [3_pBD]	$\begin{bmatrix} \frac{R^i_{j,k}-R^i_{j-1,k}}{\Delta_x} \\ \frac{R^i_{j,k}-R^i_{j,k-1}}{\Delta_y} \end{bmatrix}$		3_pBD
Diamond configuration	2D three-point stencil, first-order forward differences [3_pFD]	$\begin{bmatrix} \frac{R^i_{j+1,k}-R^i_{j,k}}{\Delta_x} \\ \frac{R^i_{j,k+1}-R^i_{j,k}}{\Delta_y} \end{bmatrix}$		3_pFD
Rectangular configuration	1D two-point stencil, first-order differences [2_p]	$\begin{bmatrix} \frac{R^i_{j+1,k+1}-R^i_{j-1,k-1}}{2\Delta_x} \\ \frac{R^i_{j+1,k+1}-R^i_{j-1,k-1}}{2\Delta_y}) \end{bmatrix}$		2_p

TABLE I: Gradient estimation formulas and corresponding configuration of receivers

and is thus more prone to configuration errors. Different first order numerical stencils were used for the 2D gradient computation. A brief mathematical basis of gradient estimation formulas and the corresponding arrangement of sensor nodes is presented in Table I. Two different hardware arrangement of wireless receivers (diamond and rectangular configurations) are shown in figure 3. Using these two configurations, five different stencils could be formed as indicated in the table I. All the receivers were placed in the same orientation so that the antenna orientation effects are negligible.

It was mentioned in [26] that, there should be a minimum spacing of $0.38\lambda_c$ (where, λ_c is the wavelength of the wireless signal) between two RSS spacial samples to obtain independent uncorrelated measurements. Therefore we spaced the receivers at least 10cm (which is $0.8\lambda_c$ at $2.4\,\mathrm{GHz}$), $\Delta_x \geq 10\,\mathrm{cm}$ and $\Delta_y \geq 10\,\mathrm{cm}$, to obtain independent uncorrelated spacial samples so that the interference between various receivers are negligible. It also means that the effects of channel noise and inter-receiver interferences are negligible between each RSS spacial sample as each sample is measured at more than $\frac{\lambda_c}{2}$ spacing.

For the Diamond configuration (Fig. 3a), $\Delta_x = 10\,\mathrm{cm}$ and $\Delta_y = 20\,\mathrm{cm}$ and for the Rectangular configuration (Fig.3b), $\Delta_x = 16\,\mathrm{cm}$ and $\Delta_y = 20\,\mathrm{cm}$.

IV. Results and discussion

In the experiments, we considered all the five different configurations mentioned in table I (5_pCL, 5_pC, 3_pBD, 3_pFD and 2_p) for the static stencils approach and the averaged 2D first order central difference configuration (5_pD) for the dynamic stencil approach. We performed ten trials for each algorithm at various distances from the transmitter both in LOS and NLOS conditions. The results of all six experimental configurations are presented in Figure 4. We can observe that the central difference method using 5 receivers (5_pC) performed better than other methods in terms of performance in the time taken to reach the optimised position and improvement in the RSS values. One of the possible explanations for such observations is the fact that there is an inherent averaging of the spatial $RSSI$ measurements in the 5_pC algorithm.

We define the $RSSI$ gain (G) as the improvement in $RSSI$ value at the new position compared to the $RSSI$ value at the previous position.

$$G = RSSI_{(X^{i+1},Y^{i+1})} - RSSI_{(X^i,Y^i)}$$

And the unit $RSSI$ gain ($G = 1\,\mathrm{dBm}$) is defined as the improvement of $1\,\mathrm{dBm}$ in $RSSI$. We normalise the results in terms of unit $RSSI$ gain so that the spatial and temporal performances of various algorithms can be compared. The spatial performance of the algorithm is measured as the distance (D) the robot moves to achieve unit $RSSI$ gain and the temporal performance of the algorithm is measured as the time taken (τ) by the algorithm moving the robot to achieve unit $RSSI$ gain:

$$D_{1\,\mathrm{dBm}} = \frac{\sum_1^S D}{\sum_1^S G},\ \tau_{1\,\mathrm{dBm}} = \frac{\sum_1^S \tau}{\sum_1^S G}$$

where S is the number of trials.

Table II summarises the time taken by the algorithm and the rectilinear (Manhattan) distance moved by the robot from its current position to achieve unit $RSSI$ gain.

Comparing the central difference method in static (5_pC) and dynamic (5_pD) mode, the former has better performance which

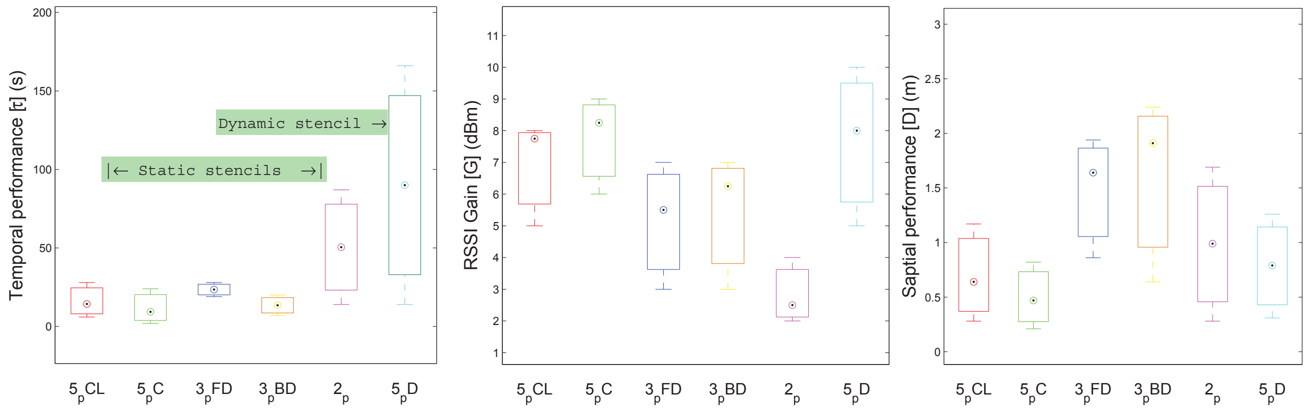


Fig. 4: Performance results of various algorithms

	5_pCL	5_pC	3_pBD	3_pFD	2_p	5_pD
Mean $RSSI$ gain $\bar{G}$ (dBm)	7.75	8.25	5.5	6.25	2.5	8
Spatial performance $D_{1\,\mathrm{dBm}}$ (m)	0.21	0.18	0.92	0.89	0.39	0.79
Temporal performance $\tau_{1\,\mathrm{dBm}}$ (s)	4.77	3.73	20.25	25.5	20.2	90

TABLE II: Comparison of temporal and spatial performance of various gradient algorithms

demonstrates that the time dependence of signal strength measurements degrades the performance of the gradient search algorithm. This then also suggests that our static stencil approach is better than previous time-dependent approaches [11], [12].

One of the advantages we obtain with static stencil (using multiple receivers at the same time) is the selection diversity gain in $RSSI$. That is, the strongest signal could be selected among the multiple receivers. When there are N receivers (which receive independent and Rayleigh distributed radio signals), the expected diversity gain in $RSSI$ expressed as a power ratio [27] has been shown to be

$$G_{Selection\ Diversity} = \sum_{k=1}^{N} \frac{1}{k}$$

Since we used 5 independent receivers for each gradient estimate, we should expect a gain of at least 2.28 dBm and we observed a minimum gain of 5.5 dBm in our trials (for 5_pC, 5_pCL and 5_pD algorithms).

According to [26], the probability of obtaining a gain of G (compared to the local average) in $RRSI$ is

$$\mathrm{Prob(G)} = 1 - \left|1 - e^{-10^{(G/10)}}\right|^5$$

This means that, when the average RSS is -70 dBm (in the NLOS region, shown in figure 2c), we can achieve a gain of at least 5 dBm at 80% probability with 5 independent samples (using 5 receivers), which was proved in our experimental results. Therefore, it is possible to improve the wireless communication performance even in NLOS region.

The results show that the central difference methods (5_pC and 5_pCL) can be used for computing gradients in RSS using spatial diversity concept which could then be used to move the robot to the local strongest signal location to improve the communication performance. The algorithms using 5 receivers demonstrated better performance than the algorithms using 3 or 2 receivers which shows the importance of having multiple receivers on-board the robot for achieving better performance compared to single receiver. Also, it is found that the static stencil 5_pC (time-independent sampling) methods work better than dynamic stencil 5_pD (time-dependent sampling) methods in terms of time and energy performances. This proves the time dependency of RSS measurements even though the spacial samples are uncorrelated.

Another advantage of using multiple receivers on-board the robot is that it reduces the chances of failure in wireless communication or local interference (signal blocking due to deep fading) to one of the receivers without blocking the reception on the entire system. Hence there is an inherent advantage of redundancy and fault-tolerant mechanisms in our approach. In addition to device redundancy, there is also a possibility of algorithmic redundancy. For instance, the diamond configuration arrangement with 5 receivers can also be used for 3_pFD and 3_pBD in addition to 5_pCL algorithm. On top of the advantages mentioned earlier, the algorithms are acting in the application layer (and not in the physical layer) and hence gives flexibility in designing improved wireless communication system without complex design changes in the hardware.

The Zyxel NWD2105 receivers each consume around 1.5 W at peak transmit power. Therefore, when we use 5 receivers, the total communication power is around 7.5 W, compared to 100 W for computing and motion power in the Youbot. However, it should also be noted that, not all the receivers need to be active at the same time and the receivers in idle state consume less than half of the peak transmit power.

Each wireless receivers that we used costs around 10 €and hence are less expensive than v,m;. a customised hardware design using directional antennas on a single receiver.

V. CONCLUSIONS AND FUTURE WORK

We proposed decentralised, time-independent, spatial diversity based, wireless signal strength optimisation methods using multiple receivers on a wireless relay robot to improve network reliability and coverage range in challenging environments such as underground scientific facilities where the reflections, interferences and multi-path effects of radio signals make wireless communication unreliable. The mobile relay robot's position is optimised using gradient ascent algorithms to receive the best RSS subject to local maxima. We experimentally demonstrated the performance of our algorithm in the ECN3 tunnel facility at CERN. The time-independent spatial sampling methods are observed to be more efficient than time-dependent methods. In our experiments, the gradient search method based on averaged central difference algorithm performed better than classical central difference and forward/backward difference algorithms in terms of time taken and improvement in RSS.

Using multiple wireless receivers also provides an advantage of having redundant networks, with which the chances of wireless network failure could be reduced and the possibilities to recover from failure situations could be increased. The main challenges in extending the proposed method to multiple relay robots are the development of a cooperative framework to coordinate the relay robots and integrating the proposed method with the existing localisation techniques which we plan to address in our further work.

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