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**PAPER TYPE (Research paper)**

# Impact of Beamforming in terms of Capacity in Wi-Fi Networks

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## Article Info

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## Abstract

Our study focuses on the impact of beamforming in terms of capacity. Deploying Wi-Fi networks involves a range of techniques and considerations, including equipment selection and access point placement. In this paper, we discuss the different techniques for Wi-Fi deployment, our Wi-Fi deployment scenarios, and the factors involved in calculating the number of access points, taking into account capacity based on the application requirements. In this paper, we evaluate three different deployment models: data rate independent, data rate dependent, and edge deployment. We conduct our tests through simulation and derive an empirical model by offering a generalization of our approach for any field size and comparing it to simulation results.

In the context of autonomous robots for smart environment, we explored deployment strategies that utilize beamforming to enhance communication range and quality. Our strategy involved determining the required number of access points for different MIMO systems across two deployment types (grid and edge deployments). The deployment types took into account the challenges associated with deployment in specific fields. Additionally, we evaluated, through simulation, our deployments for different application requirements to emulate a control station taking control of a robot in the field. After gathering simulation results, we developed an empirical model to obtain results for any field size, and the simulation result demonstrated the accuracy of the model. Our study highlighted the trade-offs between deployment cost and complexity versus network performance by using NS3 software.

## Introduction

Traditionally, access points have been equipped with omnidirectional antennas, which are so named because they send energy in all directions [1]. Frequently, omnidirectional coverage will be shown as a circle on an overhead-view map, centered on the AP. Omnidirectional antennas are cheap, and more importantly, they spray radio waves in every direction, freeing the AP of the need to track each client. As long as the client is reachable in some direction, the signal from the AP will get there.

An alternative method of transmission is to focus energy toward a receiver, a process called beamforming [2]. Provided the AP has sufficient information to send the radio energy preferentially in one direction, it is possible to reach farther. Due to the usage of internet platforms in a variety of areas, wireless systems with high data rates and adequate channel capacity are in great demand. These requirements

are usually incompatible with single-input and single-output (SISO) antennas. As a result, multiple-input and multiple-output (MIMO) printed antennas, a new form of antenna design, has emerged as a suitable candidate for high-speed communication technologies [3,4]. Video transmission techniques that exploit path diversity have been studied at length [5] for the wire line case. In parallel with these developments, the improvements associated with MIMO systems at the physical (PHY) layer have been thoroughly investigated in recent years [6-11]. However, when MIMO architectures are coupled with typical wireless channel scenarios, a more varied set of error conditions results than is the case with their wire line

Doi:

counterparts.

## Performance Evaluation of Deployment Strategies

The number of access points for deployment is an essential criterion in respecting the required data rate. In real scenarios, a network includes multiple robots. Hence, a performance evaluation is necessary to help understand the impact of mobility and interference on the quality of communication. In this section, we evaluate the deployment techniques outlined in 3.3 within the context of a specific application use case involving mobile robots in a Smart Environment scenario. We conduct our tests through simulation and derive an empirical model by offering a generalization of our approach for any field size and comparing it to simulation results.

*A. Network Performance Evaluation*

We conduct a performance study for each deployment scenario. We compare the achieved performance with data rate-independent and data rate-dependent deployments. In the data rate-independent deployment, we use the maximum coverage range of access points without considering the application or the required data rate for reliable video streaming. This means that the considered range only guarantees to send data at the minimum MCM value (MCM index = 0). The number of access points deployed is the same as the ones calculated in the first case (1 Mbits/s). In the case of data rate-dependent deployment, the access points coverage is calculated according to equation 1, considering the minimum SINR value to send at the required data rate.

$$\log_{10}(d) \leq \frac{P_t + G_t + G_r - L_0 - N - s_{th}}{10\alpha} \quad (1)$$

where d is the maximum coverage distance of an access point that ensures having the data rate requirement at the edge of a coverage cell, $s_{th}$ is the minimum (target) SINR sufficient for using a MCM, which makes it possible to send data at the minimum data rate required by the application specifications, Pt is the transmitted power, Gt and Gr are the antenna gains at the transmitter and receiver respectively, N represents the noise and interference at a given time and position, L0 is the power loss at a reference point in the coverage field of the antenna at a small distance d0 from the transmitting antenna and α is the path loss exponent.

*A. Extension of the available Wi-Fi module in NS-3*

Our evaluation procedure is based on a simulation study. We used NS-3 simulator which offers a detailed module for Wi-Fi but lacks important aspects needed in our study. In this section, we discuss the features we implemented in the simulator for the sake of our study, namely the beamforming procedure, handover, and MCM negotiation. Beamforming is not implemented in the current version of the NS-3 simulator and, according to our knowledge, is not on the timetable of the designers yet. Thus, we decided to implement a beamforming behavior in the simulator. In a single data exchange, a transmitter called the beamformer starts to measure the quality of the channel used to communicate with the receiver, known as the beamformee. The result of the measurement, which is called the sounding procedure, is used to direct the energy toward the receiver. In a Single User MIMO (SU-MIMO), the main lobe represents the total energy transmitted in the direction of the receiver while no energy (depending on the accuracy of the hardware) is transmitted in other directions. This main lobe has a beamwidth that depends on the type of antenna used. What follows is a brief summary of the features that we added to the NS-3 Simulator:

- A beamforming transmission behavior. The transmission consists of a main lobe of a triangular shape directed toward the receiver with no energy in other directions.
- A handover procedure allowing the robots to switch to the access point providing a better SINR than the currently associated access point.
- Replace the beamforming sounding procedure by the airtime it takes, which is around 500 microseconds [12].
- Integration and use of the Modified Ideal Rate Adaptation Algorithm[13]. Description of Simulation Scenarios We consider that robots are sending video streams for 30% of the time. In the remaining 70%, robots send 1 Mbits/s of data. This proportion is chosen to emulate a real intervention. Indeed, this emulates the event where the robot is taken over by a human operator taking into consideration the time needed to remotely solve the issue. Multiple robots are deployed in an outdoor environment. Each robot is deployed at a random position and follows a random path. In a real-life scenario, a robot will have a predefined trajectory. Knowing the trajectories in advance would help optimize further the positioning and the number of deployed APs. However, we adopted random trajectories as a worst-case scenario.

Each scenario is repeated 60 times with different initial positions and random paths. The number of robots deployed is increased gradually from 4 to 20 in each scenario. Note that, in a typical scenario, only a limited number of robots are deployed in one field (1 to 4 robots). In this study, we focus on the challenges that will occur due to interference and channel overload in case more robots are deployed. We consider a wired link between the APs and the control station. Multiple simulations of different scenarios were carried out while varying the number of mobile robots. The simulation parameters are shown in Table 1. In the following sub-sections, we investigate the impact of the number of APs and their configurations on throughput and delay depending on the number of users in the network. The investigation includes using SISO and MIMO with a different number of antennas. The scenarios are classified according to different application requirements (high and medium-quality video streaming) and different field sizes. We evaluate two access points deployment strategies for each scenario, one considering the application's data rate requirement and the other being a classical deployment (which does not take into account application requirements). The number of access points in each simulation scenario is based on the analytical results of previous section.

Table 1. Simulation parameters table for the capacity-aware deployment.

| Parameter | Value |
|---|---|
| Simulation Time | 80 seconds |
| Runs | 60 |
| WLAN Standard | IEEE.802.11ac |
| Path Loss Exponent | 3.5 |
| Antenna Gain | 8 dbi |
| Channel Width | 60 MHz |
| Noise Level | -140 dBm |
| Reference Loss | 56.6 dB |
| Fading Factor | random(0, 3dB) |
| Mobility Model | Random Walk 2d Mobility Model |
| Mobility | 8 m/s |
| Topology Size | 1km2 |

### *B. Medium Quality Video Streaming Application*

Figure 1 show the throughput obtained in a data rate independent deployment scenario. The throughput obtained in SISO is higher than that of MIMO with beamforming. Two main reasons explain this result. First, the number of APs is larger in the SISO case (2 APs), which leads to fewer packet losses and more channel access time for each robot, as depicted in figure 2. Second, a data rate of 25 Mbits/s requires a low SINR value at the receiver, as indicated in reference [14]. Thus, robots maintain connectivity most of the time since the MCM requirement is low. The significant difference in the throughput between the 3x3 and 6x6 antenna APs is due to the beamforming gain. When using the 6x6 system, we have a gain of approximately 6 dBs, while in the 3x3 system; the gain is around 3 dBs. This gain difference has a direct impact on the power received. This means that data can be received at a higher SINR when using a 6x6 system for a given relative position between the transmitter and the receiver. Thus, a higher MCM value can be selected at certain locations, which explains the better throughput obtained in the 6x6 system case. Note the impact of interference on the performance of the network when the number of robots increases. Additional robots increase the traffic load and thus increase the interference rate and collision probabilities. Thus, a decrease in throughput occurs when the number of robots increases. Figure 3 shows the throughput obtained in a data rate dependent deployment scenario. The 1x1 system provides better throughput than the 3x3 and 6x6 systems. This explains the need for multiple APs to handle the increased density of robots. The same applies to the edge deployment scenario due to the full coverage and the close number of APs. The throughput results of the edge deployment scenario are shown in figure 5. However, the difference in the number of access points between the two scenarios is seen in the lower delay for the 3x3 and 6x6 systems as shown in figures 4 and 6 due to more channel access time combined with the beamforming gain. Beamforming gain leads to receiving stronger signals allowing the use of higher MCM values. A larger number of access points allow a better distribution of the robots among them. Results show that the beamforming gain may not have a significant added value in applications with medium data rate requirements compared to SISO systems. Furthermore, The results show no significant difference in the number of deployed APs between different systems, as seen in figure 3.13. Thus, a cost-capacity study should be made to further aid in the choice of the technology of the deployed APs.

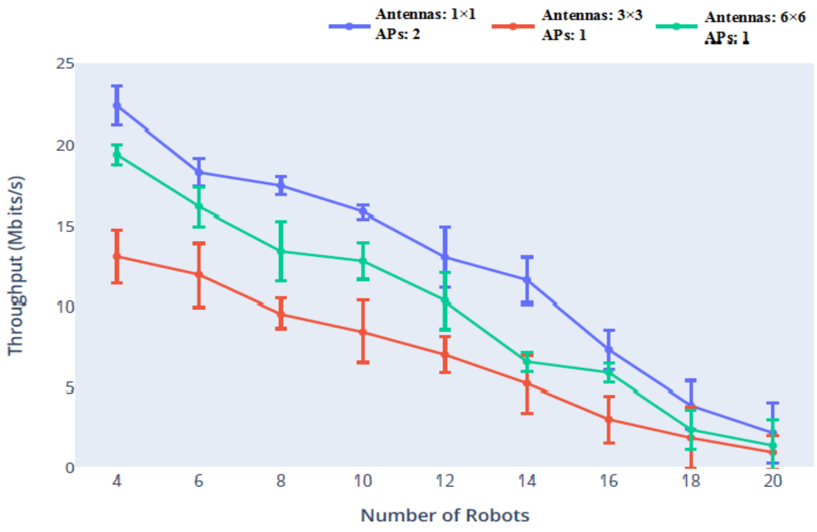


Fig.1 : Scenario 1 (data rate independent deployment): Throughput and number of access points needed for a medium quality stream.

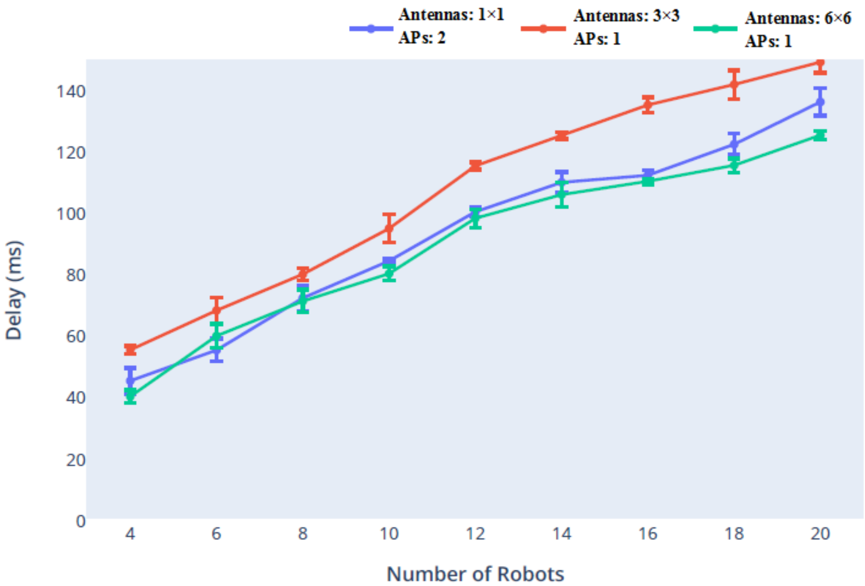


Fig.2 : Scenario 1 (data rate independent deployment): End-to-End delay for a medium quality stream.

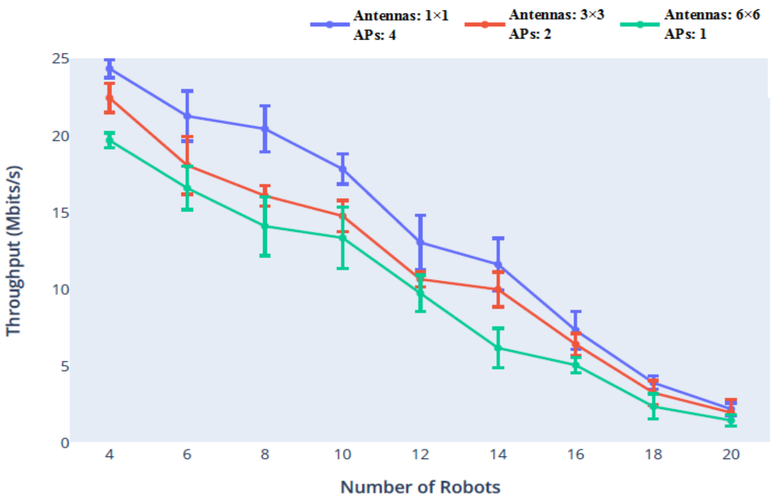


Fig. 3: Scenario 2 (data rate dependent deployment): Throughput and number of access points needed for a medium quality stream.

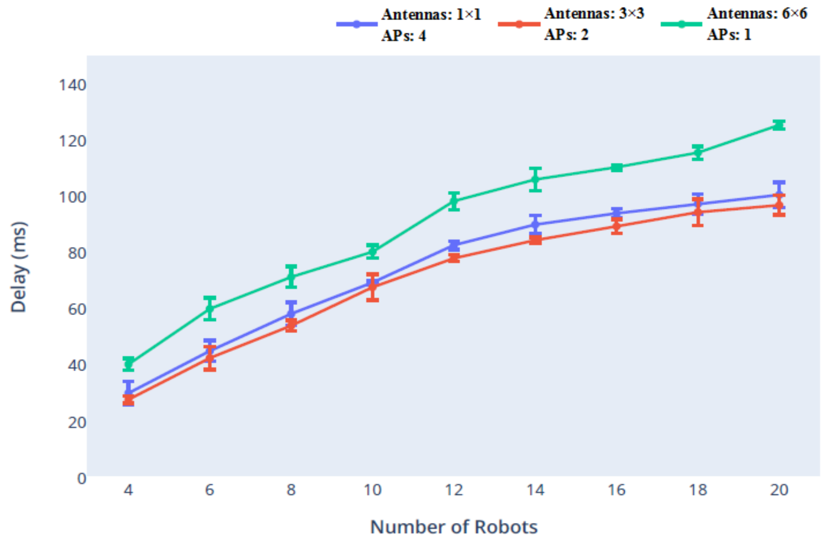


Fig. 4: Scenario 2 (data rate dependent deployment): End-to-End delay for a medium quality stream.

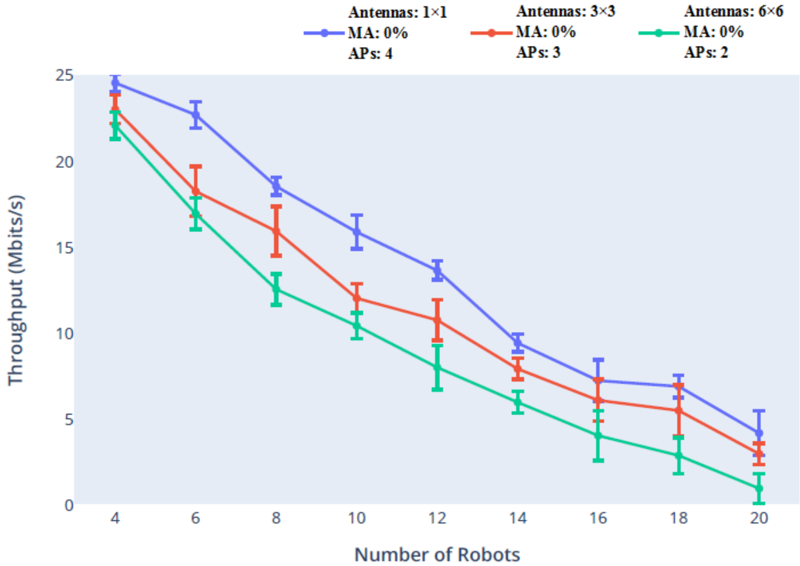


Fig. 5: Scenario 3 (edge deployment): Throughput and number of access points for medium quality stream.

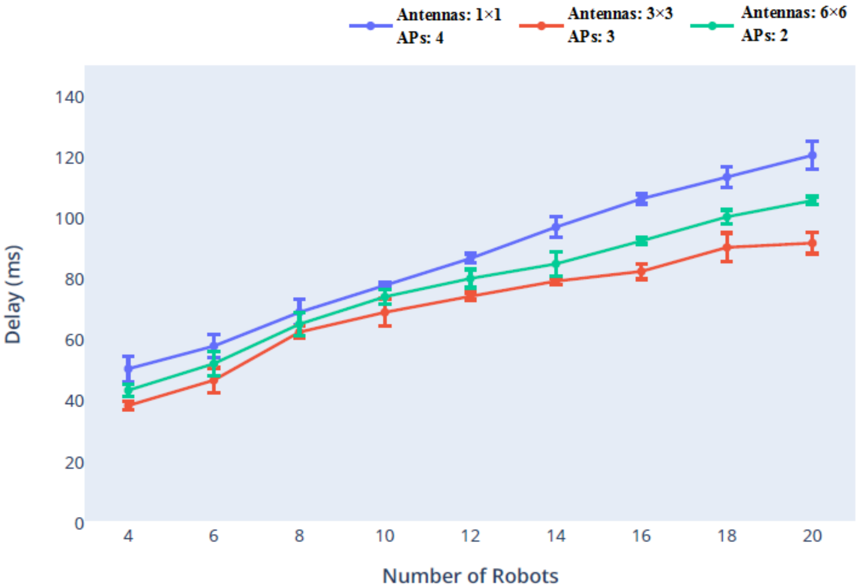


Fig.6: Scenario 3 (edge deployment): End-to-End delay for a medium quality stream.

### *B. 2.1.3. High Quality Video Streaming Application*

This section presents results for the use-case of high quality video streaming application requirements. Figure 7 shows the throughput obtained in a data rate independent deployment scenario. The robots are far from reaching the required data rate since they cannot use the target MCM in many parts of the deployment field. Although the required data rate cannot always be achieved in such deployment, the impact of beamforming and its gain is notable as it extends the range in which the MCM requirement can be satisfied. This explains the better throughput achieved by the 6x6 and 3x3 systems over the 1x1 system. The impact of beamforming on the end-to-end delay is shown in figure 8. 3x3 and 6x6 systems have the same number of deployed access points but the 6x6 system achieves a lower delay due to the selection of higher MCM values.

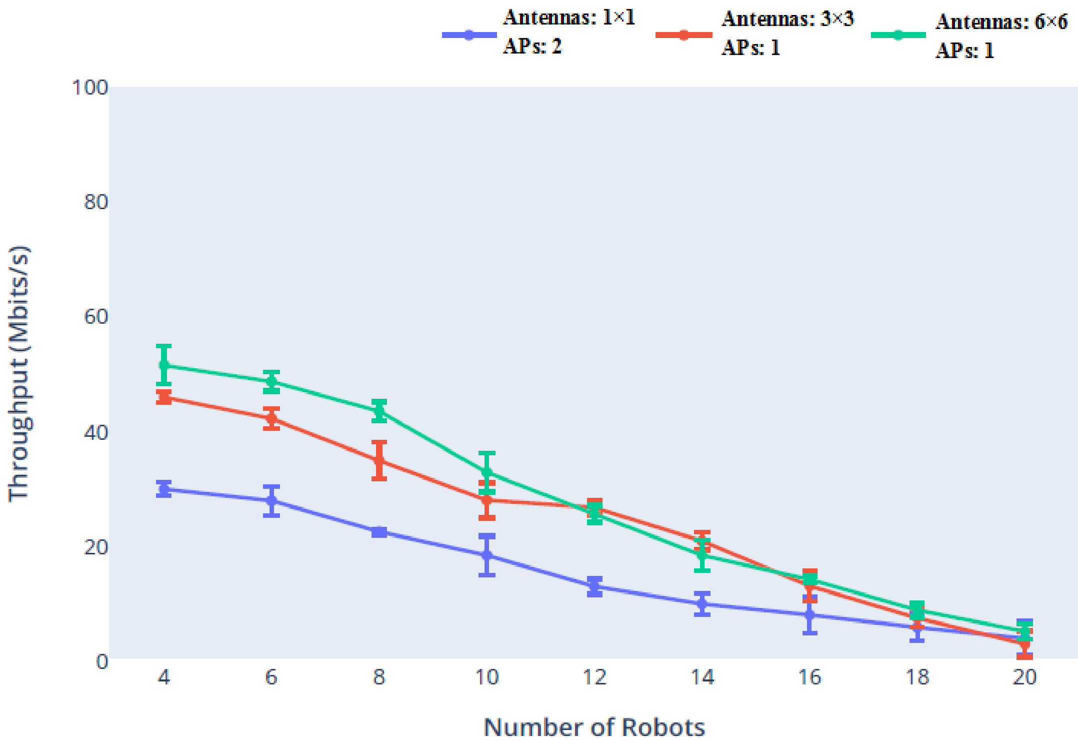


Fig. 7: Scenario 1 (data rate independent deployment): Throughput and number of access points needed when sending a high-quality stream.

In a data rate dependent deployment (scenario 2), the field is fully covered by the access points complying with the SINR requirement, hence, as shown in throughput results of figure 9. With the presence of a few robots, the performance of SISO and MIMO is close due to having a large number of access points relative to the number of robots and an SINR-dependent coverage zone of each access point. As the number of robots increases, We observe a difference in the obtained throughput due to the difference in the number of access points. More access points mean fewer robots are associated with each access point. Thus, better load balancing between access points.

The significant difference in the number of access points between the SISO and MIMO systems leads to a lower end-to-end delay in the SISO case, as shown in figure 10 due to lower channel occupancy as we increase the number of robots. The impact of a large number of access points overcomes, in this case, the impact of the beamforming gain on the end-to-end delay.

In the third scenario, access points deployed at the edge of the field, figure 11 shows the enhancement obtained from the usage of beamforming on the network performance. The network with beamforming outperformed the SISO deployment due to the difference in the non-covered area. In this type of deployment, the larger number of access points did not result in better throughput. Certain areas in the field do not allow sending at the application required MCM due to low SINR, which is the case of 3x3 and 1x1 systems. The end-to-end delay results are presented in figure 12. We have a lower delay for the 3x3 system over the 6x6 and the SISO systems due to the larger number of access points and the beamforming gain. Based on these results and the ones shown in figure 10, we conclude that as the number of access points is closer in different systems, the beamforming gain impact becomes

more significant. This causes a less end-to-end delay for MIMO systems with a larger number of antennas. Note that one of the added values of beamforming is reducing interference, especially with multiple access points deployed at the edge of the field. The better performance in 1x1 over 3x3 over 6x6 systems comes at a cost. The large gap between the number of access points required means a more expensive deployment cost for the SISO over the MIMO systems. This cost is not limited to the price of the access points but also to the increased complexity of the deployment in terms of cables and additional obstacles in the field. We should note that the theoretical beamforming gain may not be achievable in real-life scenarios due to the hardware manufacturer's design and implementation of the technology. Note that our application targets Smart Environment, where only a few robots are present in a field with predefined tasks. But if the number of nodes increases, more access points should be added to increase the capacity of the network. Another solution would be to adapt several network metrics to optimize access to the channel.

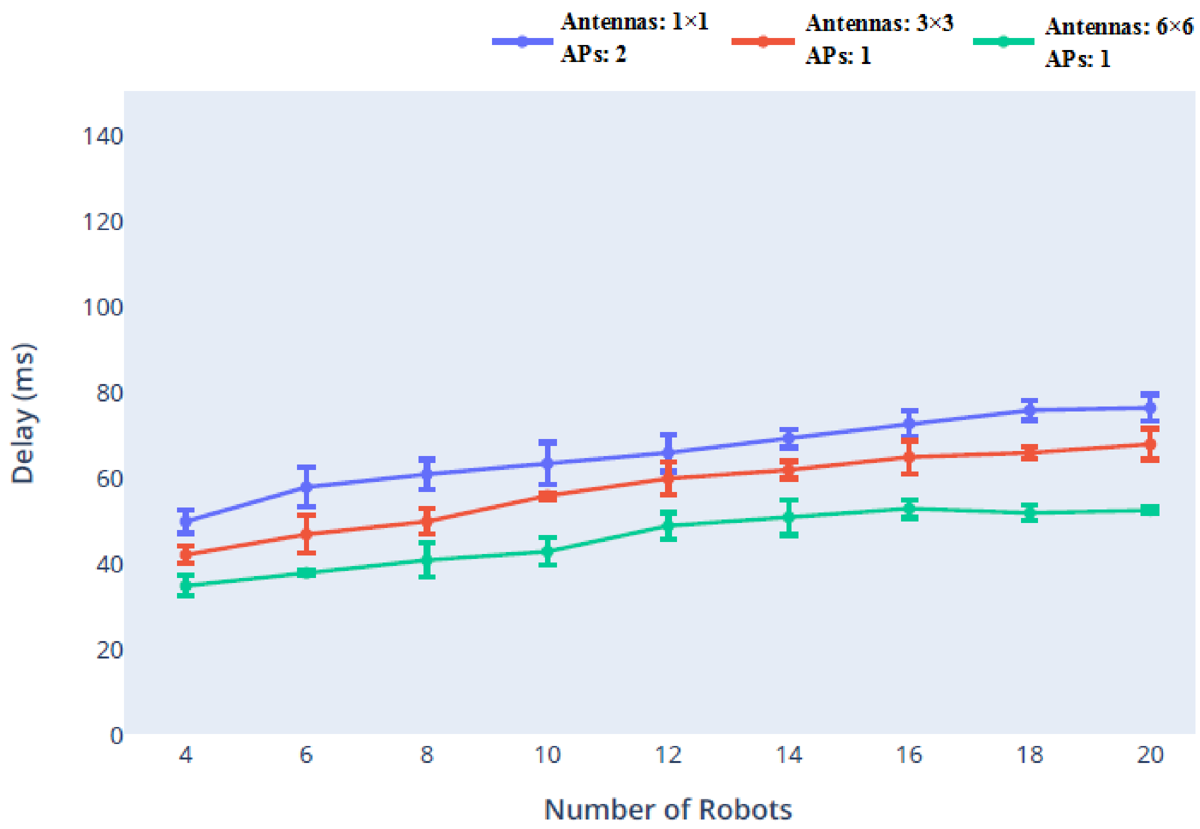


Fig. 8: Scenario 1 (data rate independent deployment): End-to-End delay for a high quality stream

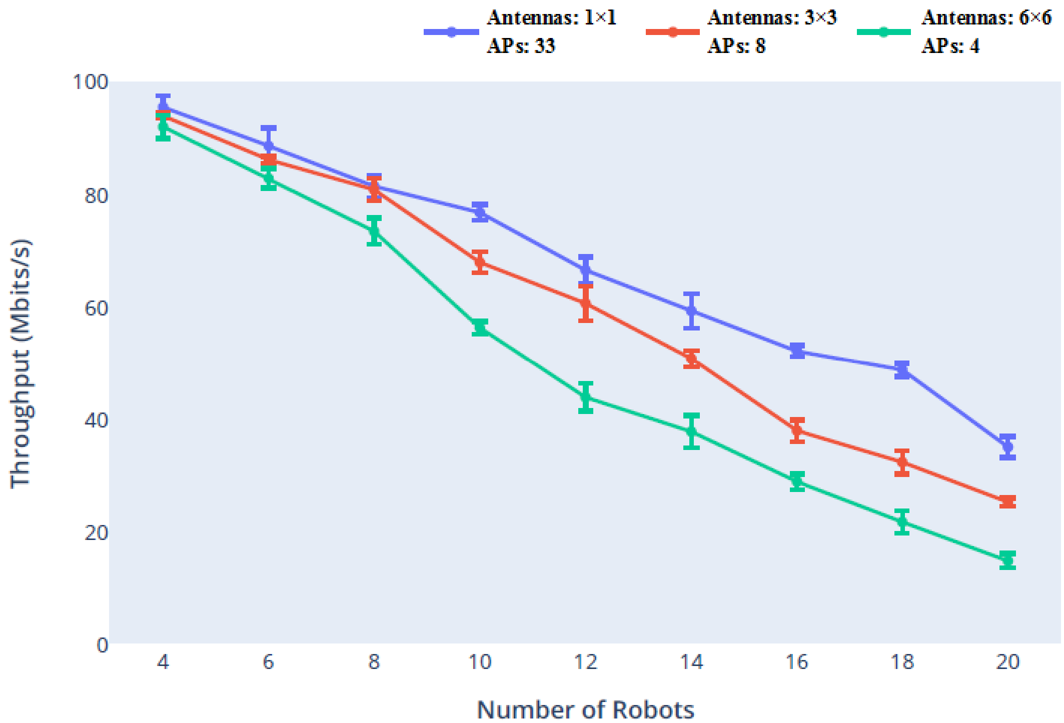


Fig. 9: Scenario 2 (data rate dependent deployment): Throughput and number of access points when sending a high-quality stream.

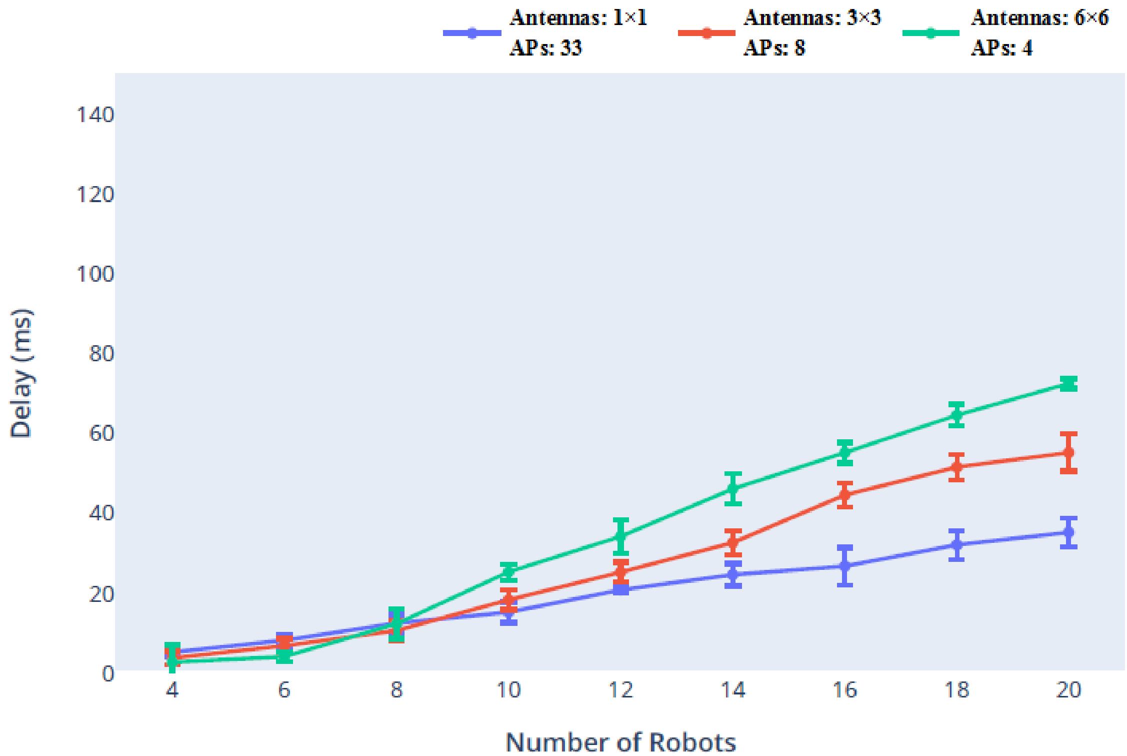


Fig. 10: Scenario 2 (data rate dependent deployment): End-to-End delay for a high quality stream.

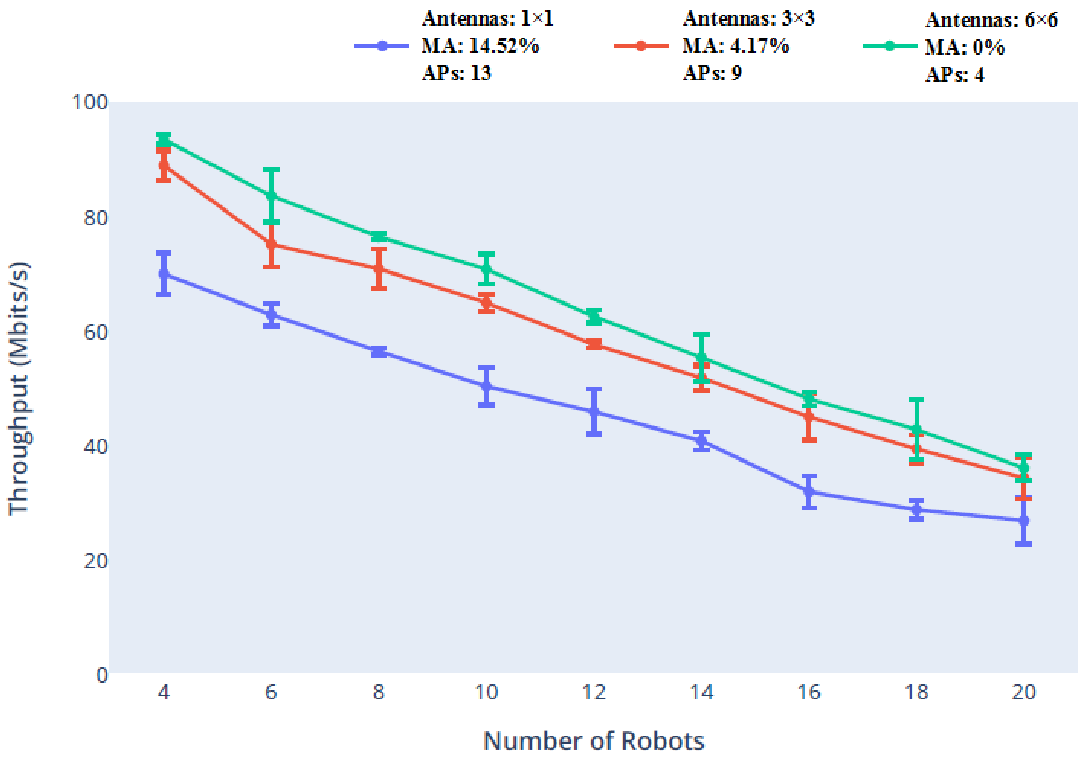


Fig. 11: Scenario 3 (Edge deployment): Throughput of the system in the special deployment with high quality streaming.

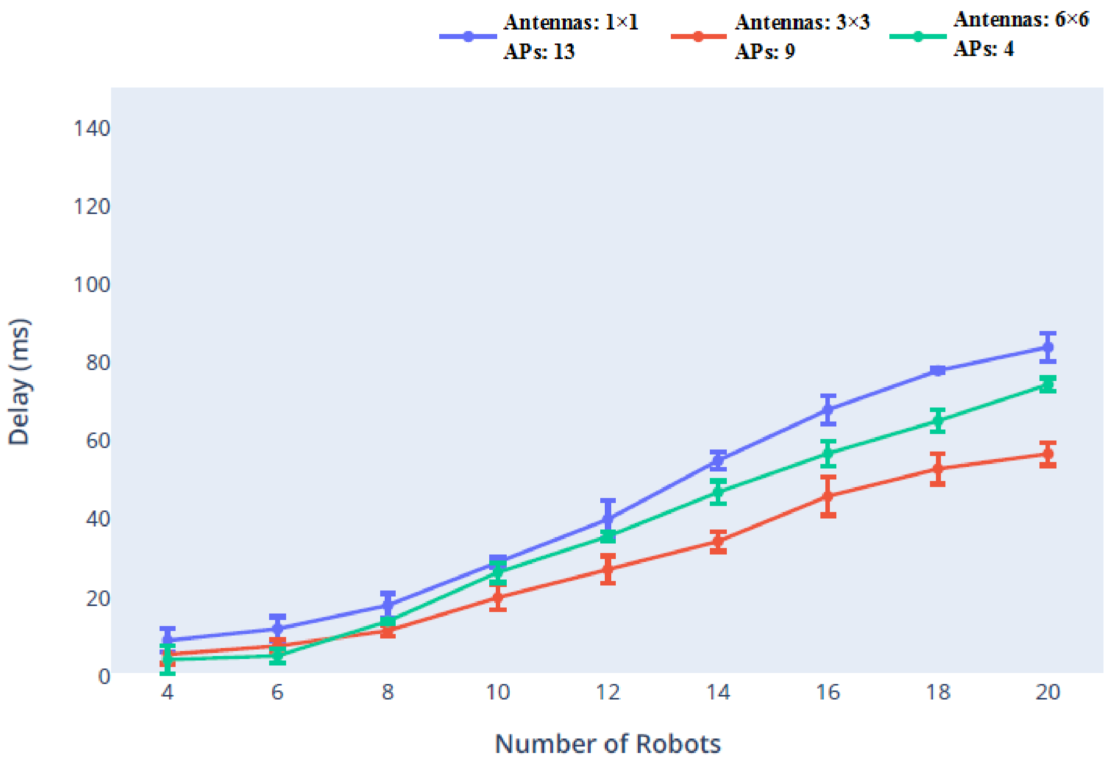


Fig. 12: Scenario 3 (edge deployment): End-to-End delay for a high quality stream

*C. 3. Empirical Performance Evaluation*

Based on the results obtained previously, we derived an empirical model to estimate the performance of the deployment relative to the field size and the number of deployed access points. This study is useful for a similar deployment strategy given a different field size. In what follows, we considered a grid data rate-dependent deployment strategy. We introduce a parameter I which represents the impact of the interference on the performance of the network. It is the ratio of the throughput obtained over the transmission data rate, also known as an offered load. I is given by the following equation:

$$I = \left(1 - \frac{thpt_{sim}}{D}\right) \quad (2)$$

where thptsim is the throughput obtained through simulation, D is the transmission data rate of the application. The deployment performance can be estimated using equation 2 if we decide to keep the same number of robots and the number of access points intact while only changing the field size. This can be done by dividing the interference impact by the area fraction Areanew/Areasimulation so that it decreases when the area of the field increases and vice versa. In reality, we have to change the number of access points when changing the field size, this will directly affect the interference impact. For instance, adding more access points will reduce interference by decreasing the density of robots per access point. To consider this change, we ran multiple simulations with the same field size and number of robots while changing the number of access points, the impact of the change in the results obtained is introduced in the following equation:

$$I_{new} = I_{original} - \alpha \delta N_{APs} \quad (3)$$

where Inew is the interference impact in the new scenario after changing the number of access points, Ioriginal is the interference impact in the original scenario, δNAPs is the difference in the number of access points between both scenarios and α is the factor calculated through multiple runs which were found to be related to the number of robots in the field as shown in figure 13. As the number of robots increases, the improvement in the performance is less significant when adding additional access points, this can be seen from equation 3. As α decreases (when more robots are introduced in the field), more access points are needed to reduce the interference impact. Using equations 2 and 3, and the values of α obtained through simulations, we tested our model for fields of areas 3Km2 and 6Km2. The estimated performance is compared to simulation results for medium-quality video streaming. Figures 14 and 15 show the estimation and the simulation results, respectively for the 3Km2 field. Simulation results include the minimum and maximum throughput values obtained throughout 40 runs. Results show that the estimation using our empirical model is close to the simulation results and falls within the min-max simulation throughput range.

We extended the area further and tested our model with a 6Km2 field. Results are shown in Figures 16 and 17. The main difference between the 6Km2 and the 3Km2 fields is the number of access points. The estimation presented in the figures is a result of the calculation of the α factor per number of robots. The graphs show that the impact of additional access points is well addressed in the empirical model. These results make performance evaluation quicker, easier, and closer to the real performance of any similar study with the same deployment strategy and application use cases.

*D. 4. Deployment Feasibility Study*

The design phase in Wi-Fi deployment is crucial for ensuring good quality of communication in the deployed network. The planning has to be realistic. In other words, one should consider the complexity of the deployment in terms of the software and the hardware availability and implementation. The deployment technique used in our study does not require any complex processing but solving simple mathematical equations. One can determine the number and the location of the access points needed to satisfy the data rate requirement of the application beforehand. Meaning that the process does not require real-time communication and the optimization could be done offline during the pre-deployment study. Increasing the number of antennas is a good enhancement to the network as it enhances the coverage and the quality of the communication, but it comes at a cost. For example: (1) the beamforming implementation differs from one vendor to another, this impacts the quality of the beamforming in terms of the expected range, the accuracy of the beams, and the beam generation time. Also, (2) the cost of MIMO access points becomes higher as we increase the number of antennas in the system

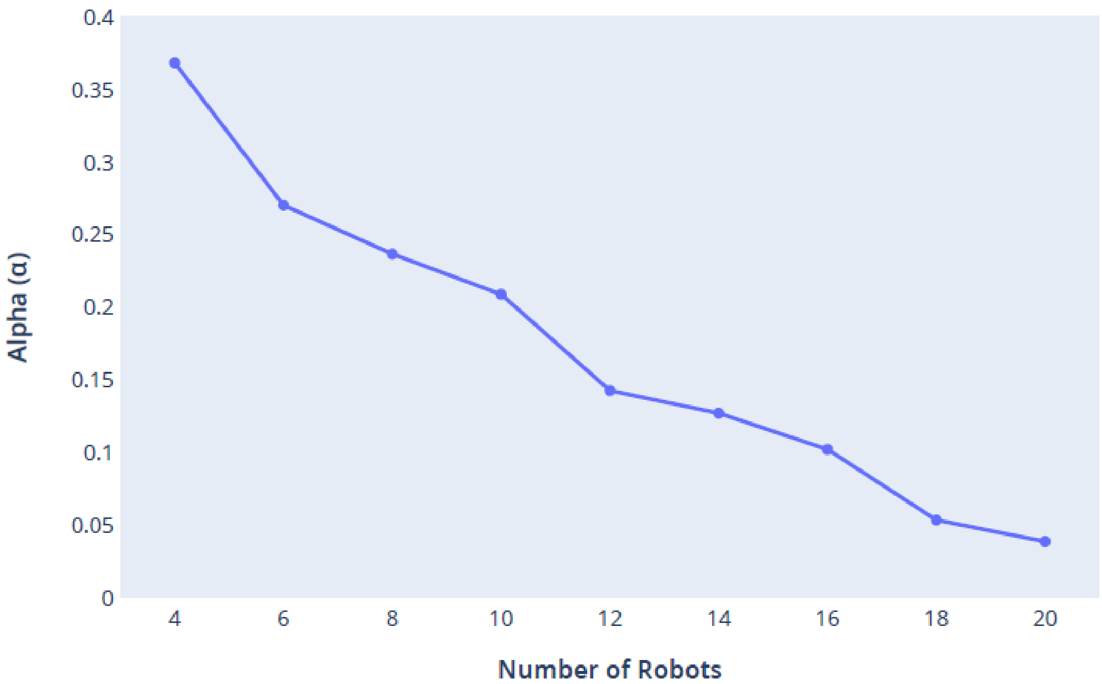


Fig. 13: Impact of the number of access points on the interference versus the number of robots in the field for a 3x3 system.

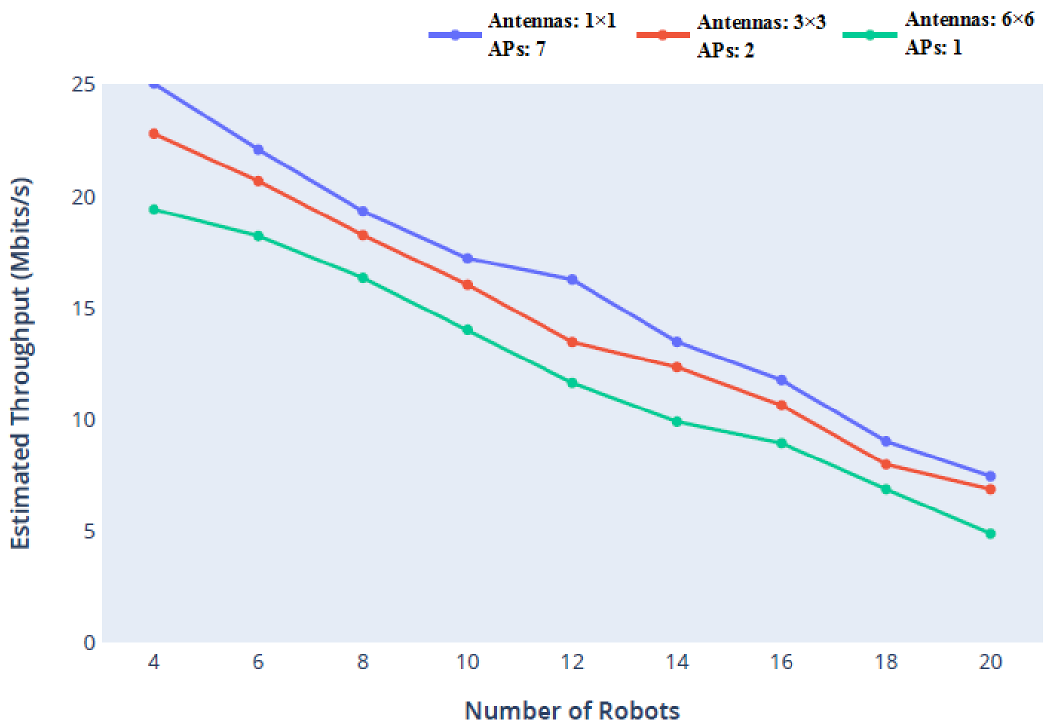


Fig. 14: Throughput obtained through estimation for a field of area 3Km2

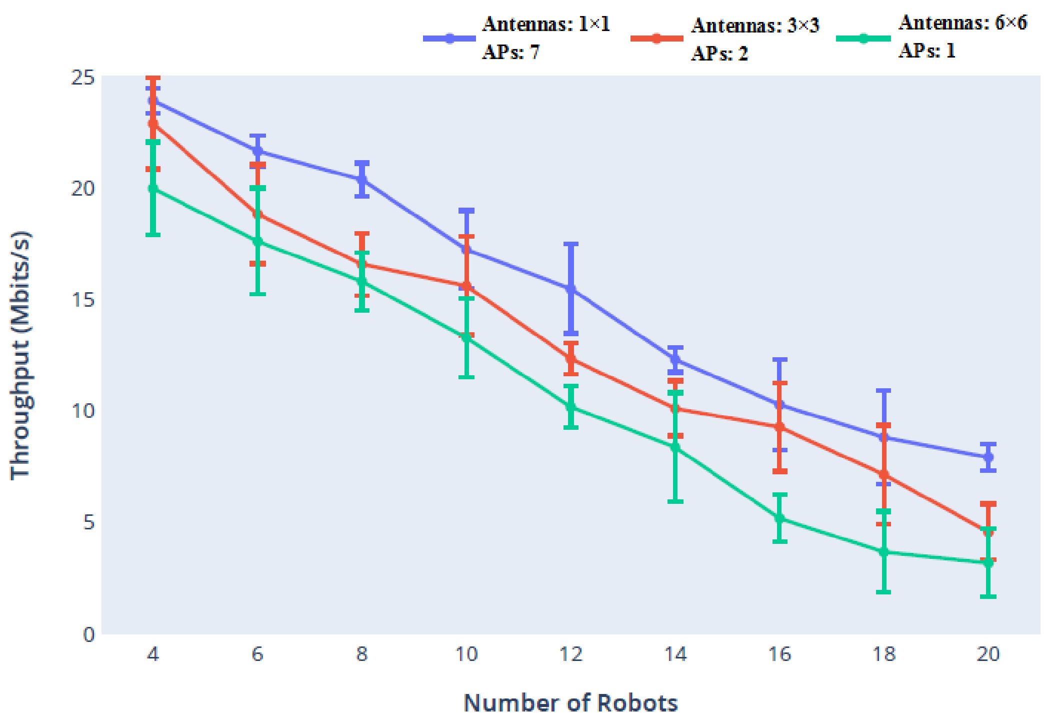


Fig. 15: Throughput obtained through simulation for a field of area 3Km2

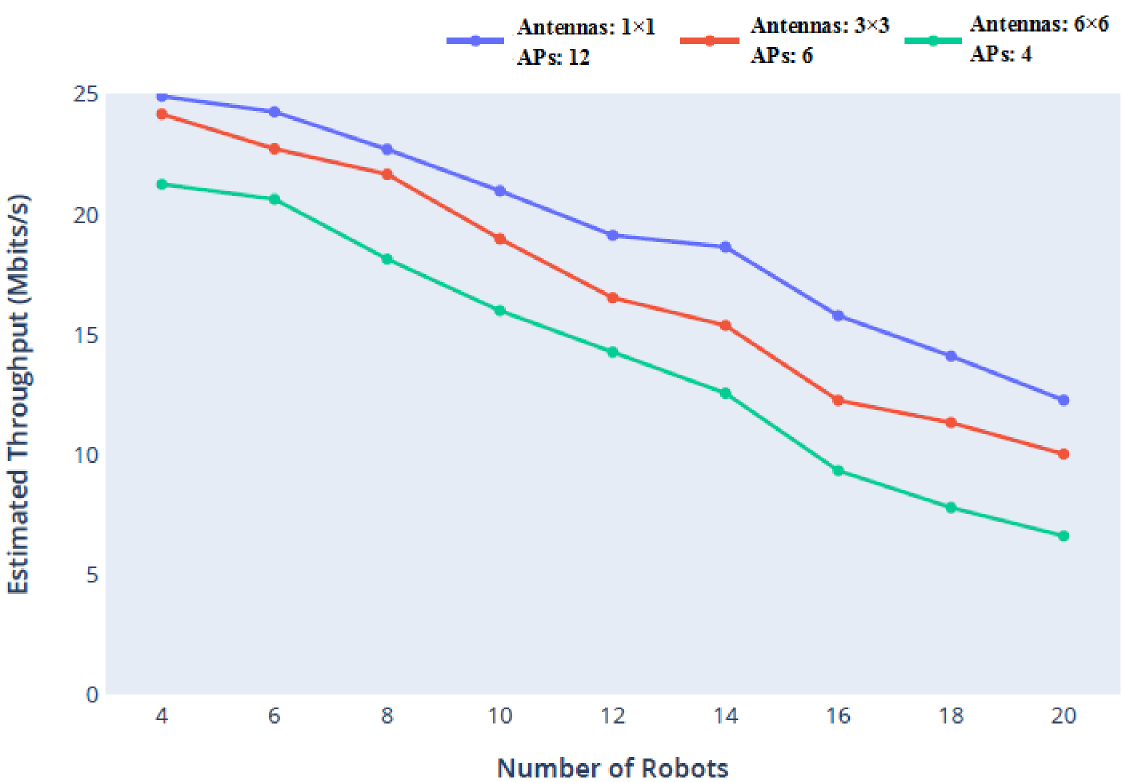


Fig. 16: Throughput obtained through estimation for a field of area 6Km2

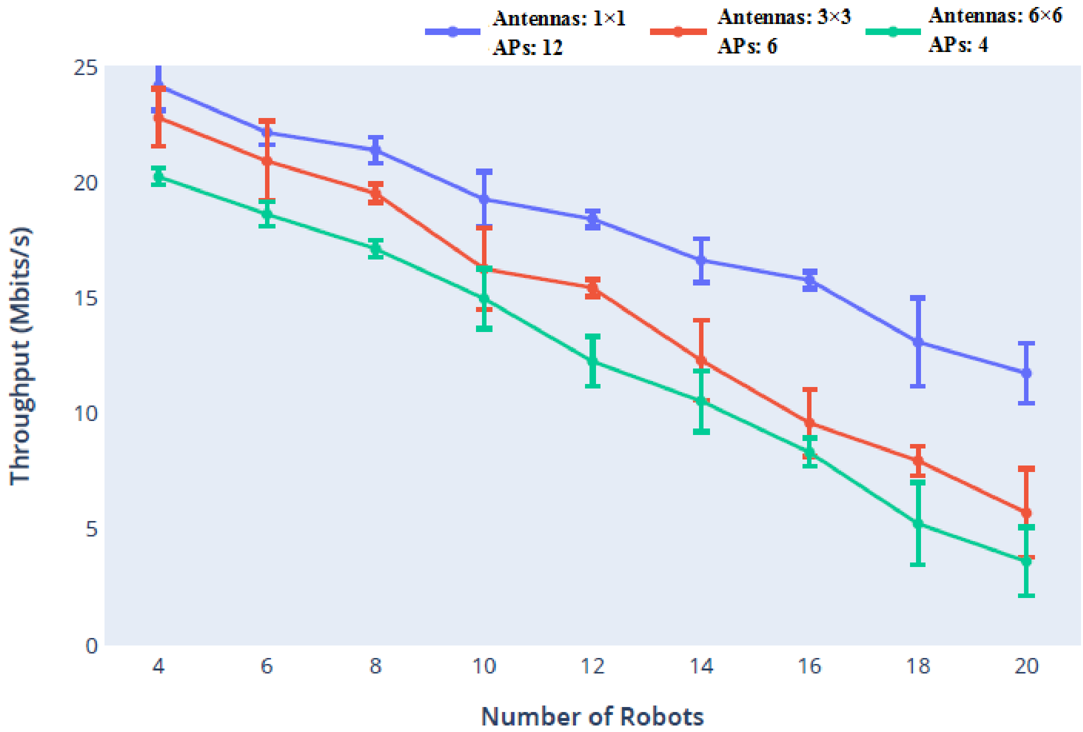


Fig. 17: Throughput obtained through simulation for a field of area 6Km2

## Conclusion

In this paper, we use rate adaptation algorithms in dense networks with focusing on metrics such as throughput and packet loss. Subsequently, we chose the best-performing algorithm and refined it to meet the standard requirements. Rate adaptation algorithms are essential as they adapt data rates over the network and greatly influence network performance. The chosen rate adaptation algorithm (Modified Ideal Rate Adaptation Algorithm) serves as the default RAA in this paper.

In the context of autonomous robots for smart environment, we explored deployment strategies that utilize beamforming to enhance communication range and quality. Our strategy involved determining the required number of access points for different MIMO systems across two deployment types (grid and edge deployments). The deployment types took into account the challenges associated with deployment in specific fields. Additionally, we evaluated, through simulation, our deployments for different application requirements to emulate a control station taking control of a robot in the field. After gathering simulation results, we developed an empirical model to obtain results for any field size, and the simulation result demonstrated

the accuracy of the model. Our study highlighted the trade-offs between deployment cost and complexity versus network performance. While deciding on a deployment plan is crucial, there remains potential for improvement across various layers of the Wi-Fi network, targeting specific challenges in Wi-Fi networks.

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