



Baština Akademije nauka i umjetnosti Bosne i Hercegovine

SMART MANUFACTURING ON THE HORIZON: A Conceptual Shift from Industry 4.0 to Industry 5.0: Industrija

Karabegović, Isak

2026

Academy of Sciences and Arts of Bosnia and Herzegovina

<https://bastina.anubih.ba/handle/123456789/875>

Preuzeto s Baštine Akademije nauka i umjetnosti Bosne i Hercegovine

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Wireless Communication Link Optimization in Cyber-Physical Systems Using Smart Sensor Networks

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Abstract: *This paper examines the optimization of wireless communication link performance for controlling unmanned aerial vehicles (UAVs), mobile robots, and remote industrial systems using a smart sensor network. Based on the analysis of sensor integration and data fusion algorithms, the proposed approach enables adaptive antenna control to maintain a stable and reliable communication link. The system utilizes measurements of position, distance, velocity, and other relevant physical parameters to improve signal quality and extend communication range. The paper also discusses the applicability of the proposed solution in cyber-physical systems and industrial environments, highlighting its potential to enhance communication reliability and operational efficiency.*

Keywords: *Wireless communication, smart sensor networks, cyber-physical systems, UAV systems, sensor fusion, adaptive control.*

1. Introduction

The field of remote control of UAVs, robots, and industrial systems has been studied for decades. Continuous advancements in telecommunications, sensors, and microelectronics have enabled the development of increasingly sophisticated RC (Remote Control) systems that provide improved control of Cyber-physical Systems (CPS), which rely on a strong synergy between computational and physical components. The primary performance parameters of wireless remote control systems are stability, range, bandwidth, and link latency, while secondary parameters include power consumption, interference immunity, scalability, compatibility, and support. Significant progress has been observed in the development of communication protocols aimed at achieving high-performance communication links. Advanced MEMS (Micro-Electro-Mechanical Sensors) enable straightforward integration into various control systems, while the application of AI (Artificial Intelligence) makes it possible to implement complex algorithms based on the fusion of different sensor measurements. High precision, compact dimensions, low power consumption, availability, and affordable cost contribute to the widespread use of various sensors delivered with standardized communication interfaces.

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Within the scope of this work, the possibility of improving RC link performance through optimization of antenna spatial orientation on both the transmitter (Tx) and receiver (Rx) sides was investigated, using an adaptive algorithm and GPS (Global Positioning System) modules for position measurement.

2. Theoretical Background / Literature Review

In the existing literature, various solutions aimed at improving the performance of remote control systems have been presented. Papers [1] and [2] discuss the application of CPS systems in Industry 4.0 and robotics. In paper [3], the authors address specific problems related to spatially distributed measurement points and sensor networks in the oil industry. In paper [4], the authors analyze modern trends in the field of sensor networks and discuss contemporary solutions developed for healthcare, navigation, rescue, intelligent transportation, social networking, and gaming applications. In paper [5], the authors address current open issues related to enabling seamless integration of WSNs (Wireless Sensor Network) with CPS designs.

In paper [6], the authors solve the problem of integrating WSNs into a spatially distributed system by implementing a WMN (Wireless Mesh Network). The focus of this article is on evaluating and improving WMN performance by increasing network throughput. A regression model is utilized as a mathematical tool to predict the number of possible links and their lengths in each proposed network topology. In paper [7], the authors study the problem of jointly optimizing BS (Base Station) placement and power control in buildings in order to prolong the battery lifetime of sensors within CPS network infrastructures, and they present an appropriate algorithm suitable for application in smart buildings and other large-scale sensor networks.

In paper [8], the authors deal with Fractional Programming (FP), a class of optimization problems in which the objective function is expressed as a ratio of two functions. Examples of such objectives include the signal-to-interference-plus-noise ratio (SINR) and Fisher information. The authors present a novel approach for accelerating the quadratic transform using Nesterov's extrapolation scheme, which is relevant for next-generation wireless networks. In paper [9], the application of quantum search algorithms for accelerating optimization tasks in wireless systems is considered, with the aim of enhancing system performance and reducing complexity. In paper [10], the authors investigate the network connectivity of wireless sensor networks using directional antennas. A new analytical directional antenna model, called the Iris model, is proposed in order to balance accuracy and complexity.

2.1. Research Objective

- Development of an appropriate method and a compact algorithm for optimal antenna alignment in a point-to-point link
- Selection of MEMS sensors enabling optimal spatial orientation of antennas on both nodes of the point-to-point link
- Selection of optimal antennas with respect to directivity and radiation pattern
- Experimental validation of the proposed method
- Analysis of the influence of sensor accuracy on link performance
- Analysis of the influence of interference on the performance of the developed point-to-point link optimization method

3. Methodology

Within the scope of this research, several scientific methods were employed. A mathematical method was used for the analytical description of the antenna spatial orientation problem. Based on the established mathematical model, a method for calculating the antenna orientation angles (Yaw and Pitch) at both ends of the point-to-point RC link was developed. Based on the proposed method, a suitable algorithm for calculating optimal angles, appropriate for software implementation, was designed. Through experimental methods, the developed approach was tested and verified using an implemented RC link prototype.

3.1 Derivation of The Method for Optimization of Antenna Spatial Orientation

In a real-world scenario, the remote controller Tx and the controlled object (or process) Rx are located at different positions, separated by a distance D that can be calculated based on the GPS positions of both nodes, as shown in Fig. 1. In the standard three-dimensional GPS coordinate system WGS84, the position of the transmitter Tx is uniquely determined by the coordinates Lat_T , Lon_T , and HT , while the position of the receiver Rx is uniquely determined by the coordinates Lat_R , Lon_R , and HR . These positions are obtained using standard GPS modules (NEO-6M) located in both the transmitter and receiver. If the transmitter position is approximately constant, it is sufficient to measure only the position of the receiver Rx while using the known or initially measured transmitter position. For easier mathematical analysis, the origin of the reference three-dimensional xyz coordinate system is placed at the Tx position, where the x-axis is directed toward the east, the y-axis toward the north, and the z-axis vertically upward. In the general case, Tx and Rx may be located at different altitudes. Therefore, in order to orient the antenna of the Tx node directly toward the antenna of the Rx node, it is necessary to calculate the Yaw angle in the horizontal x-y plane and the Pitch

angle, which represents the inclination relative to the horizontal x-y plane. In spatial geolocation systems, the Yaw angle is commonly measured relative to the north direction (0 degrees) in the clockwise direction.

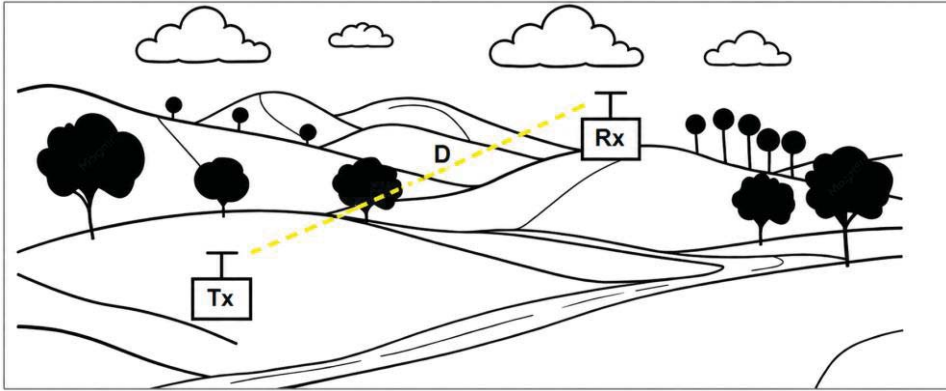


Figure 1. Positions of the transmitter Tx and receiver Rx in a real-world scenario

For the adopted coordinate-axis orientation, and based on the measured and filtered GPS coordinates of the transmitter (Tx) and receiver (Rx) shown in Fig. 2a, it is possible to calculate the horizontal Yaw angle at which the Tx node “sees” the Rx node using the following known parameters:

- φ_T - transmitter latitude in radians
- λ_T - transmitter longitude in radians
- H_T - transmitter altitude above sea level
- φ_R - receiver latitude in radians
- λ_R - receiver longitude in radians
- H_R - receiver altitude above sea level
- Yaw_{TR} - horizontal angle from Tx toward Rx in radians
- Yaw_{RT} - horizontal angle from Rx toward Tx in radians
- $Pitch_{TR}$ - vertical angle from Tx toward Rx in radians
- $\Delta\lambda_{TR}$ - longitude difference between Tx and Rx
- P_{TR}, Q_{TR} - intermediate variables used in the Yaw calculation
- D_{TR} - distance between Tx and Rx
- ΔH_{TR} - difference in altitude between Rx and Tx
- R - radius of the Earth

The horizontal angle from Tx toward Rx can be calculated using the following expression for the Yaw angle in radians:

$$Yaw_{TR} = \text{atan2}(P_{TR}, Q_{TR}) \quad (1)$$

where:

$$\Delta\lambda_{TR} = \lambda_R - \lambda_T \quad (2)$$

$$P_{TR} = \sin(\Delta\lambda_{TR}) \cos(\varphi_R) \quad (3)$$

$$Q_{TR} = \cos(\varphi_T) \sin(\varphi_R) - \sin(\varphi_T) \cos(\varphi_R) \cos(\Delta\lambda_{TR}) \quad (4)$$

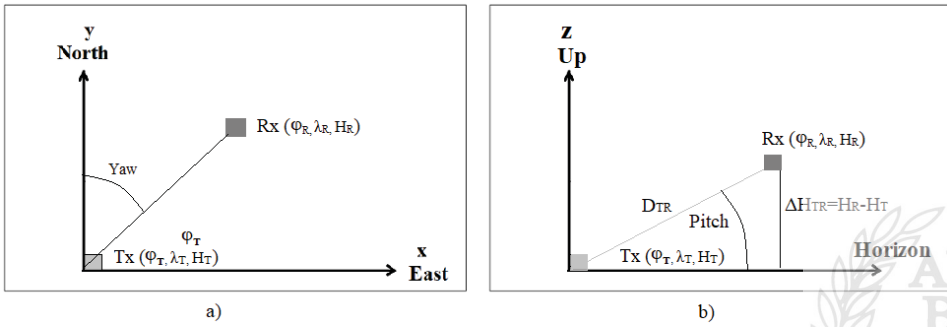


Figure 2. Positions of the transmitter Tx and receiver Rx in the horizontal x-y plane (a) and in the vertical plane (b).

The Yaw_{TR_D} angle in degrees can be calculated as:

$$Yaw_{TR_D} = (Yaw_{TR} \cdot 180/\pi + 360) \bmod 360 \quad (5)$$

while the horizontal angle under which Rx “sees” Tx is given by:

$$Yaw_{RT_D} = Yaw_{TR_D} + 180 \quad (6)$$

Similarly, based on the difference in altitude between Tx and Rx, as shown in Fig. 2b), it is possible to calculate the vertical Pitch angle $Pitch_{TR}$ at which Tx “sees” Rx in radians as:

$$Pitch_{TR} = \text{atan2}(\Delta H_{TR}, D_{TR}) \quad (7)$$

where D_{TR} is the distance between Tx and Rx, and R is the radius of the Earth ($R=6371000$),

$$D_{TR} = 2R \arcsin \sqrt{\sin^2\left(\frac{\varphi_R - \varphi_T}{2}\right) + \cos(\varphi_T) \cos(\varphi_R) \sin^2\left(\frac{\lambda_R - \lambda_T}{2}\right)} \quad (8)$$

and ΔH_{TR} is the difference in altitude between Rx and Tx:

$$\Delta H_{TR} = H_R - H_T \quad (9)$$

Finally, the Pitch angle can also be expressed in degrees as $Pitch_{TR_D}$:

$$Pitch_{TR_D} = \text{atan2}(\Delta H_{TR}, D_{TR}) 180/\pi \quad (10)$$

The proposed method enables the direct calculation of the horizontal Yaw angle and the vertical Pitch angle at which Tx “sees” Rx, based solely on the measured GPS coordinates of the Tx and Rx nodes.

3.2 Algorithm for Antenna Spatial Orientation Control Method

Based on the developed method, it is possible to design a compact algorithm suitable for software implementation on a standard 32-bit microcontroller (Fig. 3.). The algorithm can be implemented independently on both the Tx and Rx nodes. The input data for the algorithm are the GPS position of the remote node and the GPS position of the local node.

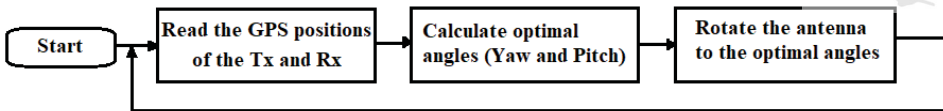


Figure 3. Algorithm of the method

The outputs of the algorithm are the horizontal Yaw angle and the vertical Pitch angle required to orient the local antenna toward the remote node. In order to optimize link performance, appropriate directional antennas with gain should be used. Antenna steering can be performed using suitable servo motors and angle measurement sensors. Thus, a microcontroller-based system with two servo mechanisms would be implemented at each node, together with sensor fusion of positional and angular data. Optimal angle estimation can be achieved based on the fusion of sensor measurements. Horizontal angle (azimuth) measurement can be performed using a digital compass, while the Pitch angle (elevation) can be measured using a tilt sensor.

3.3 Experimental Verification of the Adaptive Antenna Steering Method

Experimental measurements were conducted in a rural area outside the city. The Tx node was implemented using an ESP32-S3 microcontroller development platform operating in the 2.4 GHz WiFi frequency band, with a transmission power of 100 mW and a directional antenna with a gain of 9 dBi (Fig. 4). The ESP32-S3 microcontroller includes a 2.4 GHz Wi-Fi adapter and has sufficient processing power and memory to control the antenna direction. The NEO-6M GPS module obtains the transmitter's GPS location, while angle sensors measure the Pitch and Yaw angles. Two servo motors are used to position the antenna according to the calculated Pitch and Yaw angles. The 5V/5A power supply unit provides sufficient power for all components. The receiver (Rx) node was represented by a mobile phone equipped with an antenna gain of approximately 2 dBi. Multiple measurements were performed under two different experimental scenarios.

Scenario 1: Range measurement with a fixed antenna orientation

In this scenario, the Tx antenna was kept in a fixed direction while the Rx node was moved to record the critical Tx signal strength level of -80 dBm. The goal of this measurement was to obtain a curve representing the spatial region within which the Rx receives a stable signal from the Tx.

Scenario 2: Range measurement with adaptive antenna steering toward the receiver The goal of this measurement was to obtain a curve representing the spatial area where the Rx receives a stable signal from the Tx when adaptive antenna steering is applied.

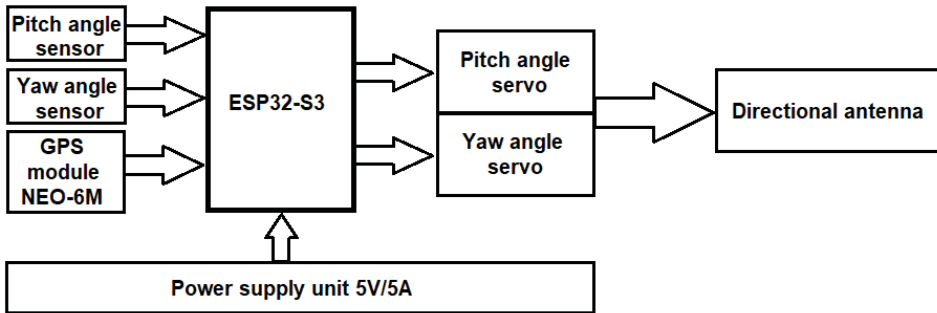


Figure 4. Block diagram of the transmitter hardware implementation

4. Results and Discussion

Based on multiple repeated measurements in both scenarios, the curves shown in Fig. 5. were constructed, illustrating the range of the Tx signal. Measurements from the first scenario are marked with empty squares. Through interpolation, a dashed line was obtained, representing the maximum Tx range (signal level of -80 dBm). According to the ellipsoidal radiation pattern of the Tx antenna, an ellipsoidal region was obtained within which a stable link was maintained, with a maximum range of 170 m. In the second scenario, with adaptive antenna steering toward the receiver, the effective communication coverage within the movement zone of the Rx node increased on average by a factor of 2–3 while maintaining a stable signal strength level of -80 dBm.

The obtained interpolated trajectory is approximately semicircular in shape. Thanks to adaptive antenna steering in both Yaw (azimuth) and Pitch (elevation), an increased maximum range of approximately 200 m was achieved. A statistical analysis of 30 repeated link-range measurements conducted under identical conditions showed a small dispersion of the experimental results. Based on the experimental results, it can be concluded that adaptive antenna steering at one or both ends of a point-to-point link can significantly increase the range of an RC link.

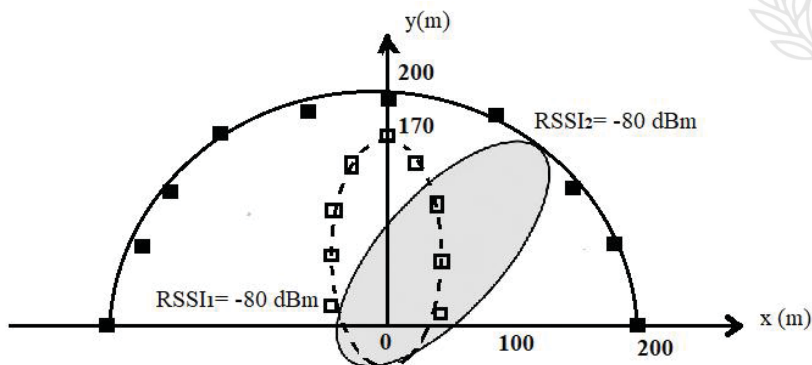


Figure 5. Graphical representation of link range with a fixed antenna orientation and with an antenna steered toward the receiver.

5. Conclusion

The developed method and corresponding algorithm have been implemented and experimentally verified under real-world conditions. Depending on the communication link usage scenario, appropriate antennas can be selected at both

ends of the point-to-point link. By using directional antennas at both ends of the point-to-point link, maximum range can be achieved. However, this requires continuous and precise antenna alignment. The achieved results are competitive with those obtained using conventional methods based on multiple antennas with different fixed orientations, where the system, through the application of an appropriate algorithm, selects the signal from the antenna receiving the strongest signal. The implementation of the proposed solution is of similar complexity to a solution employing multiple antennas on the Tx and Rx modules. As the link range is significantly influenced by terrain characteristics, interference, antenna placement, antenna gain, and weather conditions, direct comparison of the obtained experimental results with those reported in similar studies is limited.

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