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USING SMART ANTENNA FOR INTERFERENCE RESISTANT INDUSTRIAL WIRELESS SENSOR NETWORKS: A REVIEW

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ABSTRACT

Wireless sensor networks deployed in harsh and time-varying radio environments, such as those seen in industrial settings, are susceptible to radio frequency interferences that are not present in conventional wireless sensor networks used for office or home automation. Noise and other wireless interference affect network connectivity and reduce communication channel quality. Furthermore, reliability and latency, which are critical components of industrial communication, suffer. It is difficult to build wireless networks in industrial environments that can coexist with competing wireless devices in an increasingly congested frequency spectrum and are immune to signal interference. To address these difficulties, we must consider the benefits that approaches that have been effective in other application areas can bring to industrial communication. Smart antenna approaches present a viable solution for increasing the interference resistance of industrial wireless sensor networks. Integration of smart antennas into the physical layers of Industrial Wireless Sensor Network (IWSNs) can enable effective signal transmission and reception by devices, which is superior to the omnidirectional antennas now in use. This would reduce interference and boost IWSNs wireless reliability.

Keywords: Industrial wireless sensor networks, Interference, Interference mitigation techniques, Smart antenna, Smart antenna prototype

1. INTRODUCTION

The use of Industrial Wireless Sensor Network (IWSN) technology in industrial automation has gained more attention as a result of Industry 4.0. The advantages include faster deployment times and lower infrastructure costs, as well as simplicity in installation and maintenance. The network infrastructure requirements for industrial automation are more stringent and crucial, nevertheless, and include real-time data transmission, energy consumption, dependability, and fault tolerance (Soares *et al.,* 2022), (Liu et al., 2022). There are several concerns associated with radio frequency interference for these kinds of cyber-physical systems (Curiac *et al.,* 2016). Noise and other wireless interference have an impact on network connectivity and reduce the communication channel quality. Furthermore, reliability and latency, which are essential components of industrial communication, are also adversely affected. Building wireless networks in industrial environments that can coexist with competing wireless devices in an increasingly congested frequency band and are immune to signal interference is a challenge. We must take into account the advantages that approaches that have been successful in other application areas can bring to industrial communication in order to tackle these issues. In addition to the tried-and-true techniques like deterministic assignment multiple access or random multiple access, equipping sensor nodes with smart antennas is a workable approach to overcome interference issues (Chiwewe *et al.,* 2015). Smart antennas have advantages over the current method of using omnidirectional antennas, including enhanced transmission quality, increased energy efficiency, and fewer hops due to an increased transmission range, as well as interference mitigation.

Previous works in literature categorized interference in IWSNs broadly into narrow and broadband. This work describes Ultra Wide Band (UWB) interference as an addi-

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tional category. UWB cannot be classified under broadband interference as they have a potential to completely cause a Denial of Service (DoS) in a network**.** In this paper, we begin a discussion of the advantages and disadvantages of utilizing smart antennas in industrial settings, concentrating on various interference sources, and existing mitigation techniques. Following that, an outline of the smart antenna technique is provided. This is followed by research into smart antenna prototypes for industrial applications. Finally, we discuss the benefits and limitations of the smart antenna strategy in IWSNs.

2. INTERFERENCE IN INDUSTRIAL WIRELESS SENSOR NETWORKS

Interference is one of the most serious problems affecting wireless reliability; it occurs when the transmission of a radio signal generated by a network node is affected by the radio signals of another node. The main causes of interference impacting data reliability and effective operating range in wireless communication systems are multipath fading, radio interference, and noise. The following sections describe interference sources, types, and conventional mitigation techniques in industrial WSN.

2.1. Sources of Interference in IWSNs

The various sources of interference in IWSNs are:

2.1.1 Noise

This is classified into white noise and impulse noise.

A. White Noise

White noise is a type of noise made by mixing sounds of different frequencies (Deepa *et al.,* 2018). This noise affects wireless communication systems and is often represented by Additive White Gaussian Noise (AWGN). The chance of detecting bit mistakes in the presence of white noise is a typical metric for measuring communication system performance (Chaudhari, 2022).

B. Impulse Noise

A quick burst of power with a virtually flat frequency response across a spectrum range is known as impulse noise. It is defined as a voltage increase of 12 dB or more above the Root Mean Square (RMS) noise lasting no more than 12 ms (Price and Goble, 1993). Motors, heavy machinery, ignition systems, inverters, voltage regulators, electric switch contacts, welding equipment, and other industrial equipments are all major producers of implusive noise.

2.1.2 Narrowband Signal Interference

Narrowband signal interference refers to the source of the interference having a narrow bandwidth (or spectral width). Narrowband signal interference operate with signals that have a Fractional Bandwidth (B_F) of **(**$0.00<B_F \leq 0.01$**)** or $0\%<B_F \leq 1\%$ of the given system bandwidth. The fractional bandwidth of a signal is given as (Sabbath *et al.,* 2005):

$$B_F = \frac{f_h - f_l}{(f_h + f_l)/2} 100\% \quad . . . \quad (1)$$

where, f_h and f_l , respectively are the highest and lowest components of the signal. The interference could be caused by several narrowband signals. The interfering signals' baseband expression is defined by (Cheffena, 2016).

$$J(t) = \sum_{n=0}^{N-1} \sqrt{2}\, \alpha_n \exp\{j\phi_n(t)\} \quad . . . \quad (2)$$

Where α_n is a randomly distributed independent variable with $E[\alpha_n^2] = J/N$ where J is the total interference power and N is the total number of the interfering signal. Parameter $\phi_n(t)$ is the phase of the nth interfering signal uniformly distributed within the range [0, 2π]. The sources of narrowband interference in industrial WSN are radio and TV transmitters, cellular telephone, power line hum, signal generators etc. (Low *et al.,* 2005).

2.1.3 Broadband Signal Interference

Broadband signal interference, often known as wideband signal interference, refers to the source of the interference having a wide bandwidth. Broadband signal interference operates with signals that have a Fractional Bandwidth (B_F) of ($0.01<B_F \leq 0.25$) or $1\%<B_F \leq 25\%$ of the system bandwidth (Price and Goble, 1993). Broadband interference of sufficient strength can cause

severe interruption of communication in a system. The sources of broadband interference are electric motors, thermostats, power lines, zappers, computers, monitors and televisions etc (Chiwewe *et al.,* 2015).

2.1.4 Ultra-wideband Signal Interference

Ultra-Wide Band (UWB) signal interference refers to the source of the interference having an ultra-wide bandwidth. UWB band signal interference operates with signals that have a fractional bandwidth (B_F) of ($0.25<B_F \leq 2.00$) or $25\%<B_F \leq 200\%$ of the system bandwidth (Price and Goble, 1993). For UWB interference, a random process with a constant power spectral density over the whole bandwidth of the signal can be written as (Cheffena, 2016):

$$P_i = \int_{-\infty}^{\infty} S_i(f)df = BI_0 \qquad \dots \qquad (3)$$

where B is the bandwidth and $S_i(f)$ and I_0 are the spectrum and spectral density of the interfering signal respectively. UWB signal can completely cause a Denial of Service (DoS) in a network**.** Noise and narrowband signal will most often cause only disturbance in a network. However, if a time-delayed mixture of narrowband signals sweeps over a band it can act as a UWB signal completely causing a DOS for the network (Sabbath *et al.,* 2005). The sources of ultra-wideband interferences are industrial microwave ovens, multiple arc welders and multiple high Horse Power (HP) motors etc. (Chiwewe *et al.,* 2015). Table 1 shows a classification of devices and signals based on bandwidth. Fig. 1 shows different interference sources found in industrial environments.

2.1.5 Multipath Signal Interference

Multipath signal interference is defined as a received signal that is a superposition of numerous delayed and scaled copies of the original signal (Yao, 2010). It creates Inter Symbol Interference (ISI) at the receiver, which can lead to significant error rates in symbol detection, resulting in data corruption. It also causes multipath fading, which occurs when many versions of a sent signal reach a receiver as a result of multipath (Chiwewe *et al.,* 2015).

A. Multiple reflections from mainly metallic structures, factory floors and walls in the surrounding environment.

B. Random/periodic movement of people/objects may also cause time-varying channel conditions. This causes a phase variance between different copies of the signal, resulting in destructive interference and ultimately reduced signal strength, lower network throughput and reduced communication range.

Table 1. A Classification Scheme For Devices/Signals Based On Bandwidth (Sabbath *et al.,* 2005).

Radar/ Communications	Electromagnetic Interference	Fractional Bandwidth	Band Ratio
Narrowband (NB)	Hypoband (HB)	$0.00<B_F \leq 0.01$	$0.00<b_r \leq 1.01$
Wideband (WB)	Mesoband (MB)	$0.01<B_F \leq 0.25$	$1.01<b_r \leq 1.29$
Ultra-Wide Band (UWB)	Sub-hyperband (SHB)	$0.25<B_F \leq 1.50$	$1.29<b_r \leq 7.00$
	Hyperband (HB)	$1.5<B_F \leq 2.00$	$7.00<b_r \leq \infty$

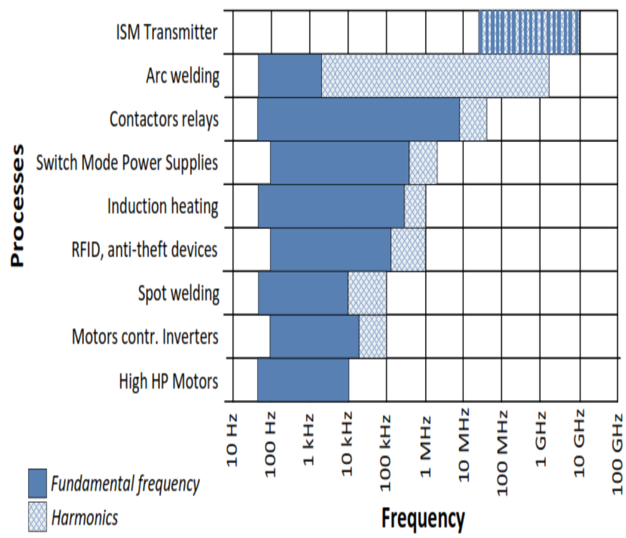

Figure 1: Frequency of Different Processes and Interference Devices in Industry (Chiwewe *et al.,* 2015).

2.2. Interference Mitigation Using Traditional Techniques

The major traditional interference mitigation techniques for IWSNs are outlined below (Chiwewe *et al.,* 2015):

1. Forward Error Correction (FEC) and Automatic Repeat request (ARQ)

2. Deterministic Assignment Multiple Access

Examples of deterministic assignment multiple Access techniques are: Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), CODE Division Multiple Access (CDMA) and Spatial Division Multiple Access (SDMA).

3. Random Multiple Access.

Example of random multiple access techniques are: ALOHA and Carrier Sense Multiple Access (CSMA)

4. Spread Spectrum Techniques

5. Ultra Wide Band (UWB)

6. Diversity Schemes and Transmit Power Control

3. SMART ANTENNA SYSTEM

3.1. Smart Antenna

A smart antenna is a system that consists of many antenna elements and a digital processor that is used to adjust the radiation. A Smart Antenna (SA) may dynamically adjust its antenna pattern to respond to noise and interference in the channel, as well as to prevent multipath fading effects on the signal of interest. This can considerably increase the performance parameters of a wireless system (such as capacity). The signals received at each antenna are intelligently integrated to increase the overall performance of the wireless system, with the opposite process occurring during transmit (Li, 2009). The functional block diagram of a smart antenna is shown in Figure 2.

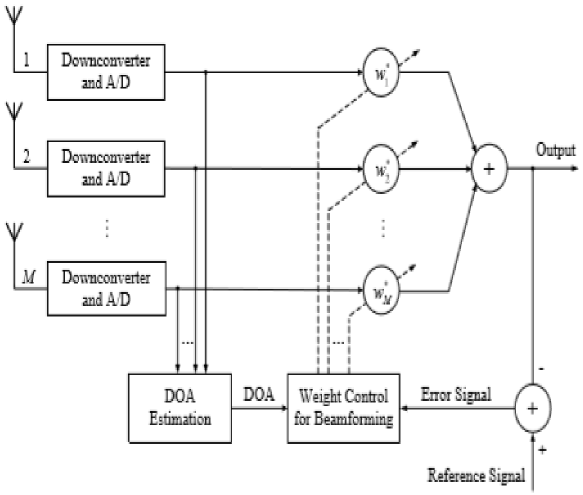

Figure 2: Functional Block Diagram of Smart Antenna System (Li, 2009).

A smart antenna system's functionalities are primarily split into two categories (Jain and Sharma, 2015):

3.1.1 Direction of Arrival (DoA)

This is used to estimate and determine the amount of incoming signals, the DoA method is employed. The DoA algorithm then classifies the signal to determine which signals are from the user and which are interfering signals.

3.1.2 Beamforming Algorithm

This is used to create an antenna pattern with the primary beam pointing in the direction of the user and its nulls decreasing the influence of interfering signals.

Smart antennas are classified into two kinds (Winters, 2006):

A. Switched Beam

Switched beam smart antennas combine the signals of several antennas to produce a number of specified fixed beam patterns. It includes a basic switch capability for switching between individual directional antennas and preconfigured array beams. It uses the switched beam formation approach to direct the beams in one or more specific directions. The switched beam smart antenna will choose the best one for the provided directions. This technique is less versatile, but it is a straightforward design that can be used for a variety of purposes.

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B. Adaptive Array

Adaptive Antennas (AAs) are a group of antennas that can dynamically change their antenna pattern to adjust for noise, interference, and multipath. AAs can be used to improve the quality of received signals and to form transmission beams. AAs, as opposed to regular antennas, focus broadcast radiation into a narrow beam. It optimizes the way signals are transmitted over space in real-time by focusing the signal on the desired user and "steering" it away from other users in the same cell as well as neighbouring or distant cells using the same channel.

Fig. 3 depicts two types of smart antennas in receive beam shaping mode. It could potentially be in transmit mode, where signals are sent out rather than received by the antenna.

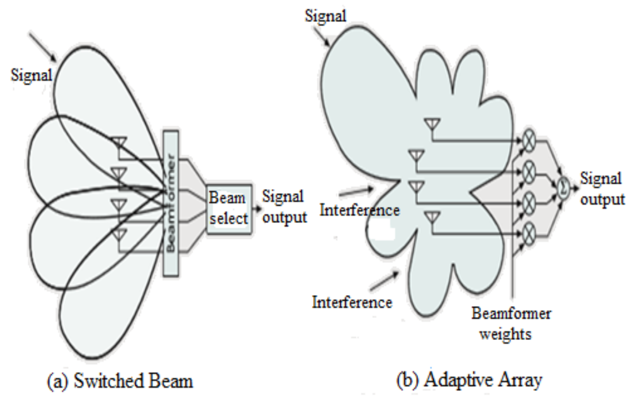

Figure 3: Types of Smart Antennas (Winters, 2006)

A comparison of switched beam and adaptive antenna array technologies is provided below in Table 2. An adaptive array has a more adaptable radiation pattern and can continually redirect its beam in any direction. Adaptive arrays necessitate more intelligence and can better determine their surroundings. Because they can effectively suppress unwanted interferences from all directions, they are usually more precise and efficient than switched beam smart antennas.

There are several techniques for implementing smart antennas (Mansour, 2016). Figure 4 shows a generalized classification of these implementation techniques.

Table 2. Differences between switched beam antenna and adaptive antenna

Switched beam Antenna	Adaptive Antenna
1. Uses multiple fixed directional beams and algorithms for the beam selection	Antenna beams adaptively track signal direction; a null can be placed in the direction of an interferer.
2. Intra-cell hand-offs between beams have to be handled	No intra-cell handoff problems since beam continually are track by user.
3. It requires only moderate interaction with the base station receiver.	It requires more interaction with the base station
4. It has a relatively low capacity.	It may have greater capacity when compared to the switch beam antenna.
5. It is less cost and complex.	More intensive signal processing is needed hence more expensive and complex.
6. It cannot mitigate multipath interference with DoA close to that of the desired signal.	It can mitigate all kinds of multipath interfering signals.
7. It is unable to take advantage of path diversity by combining coherent multipath	It can take advantage of path diversity by combining coherent multipath

3.2. Switched Beamforming and Adaptive Beamforming Techniques

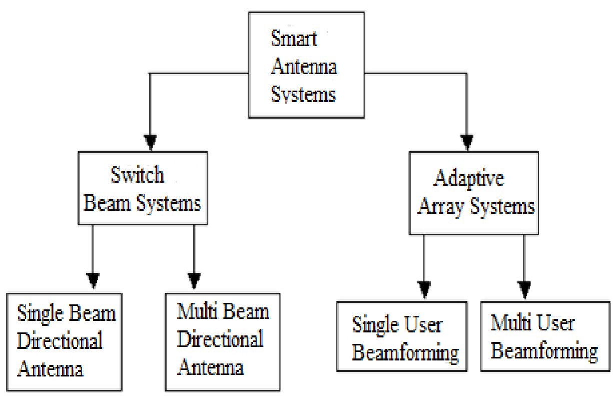

Figure 4: Classification of Smart Antenna Techniques (Mansour, 2016).

3.3. Smart Antenna and Omni-directional Antenna

Omnidirectional antennas have traditionally been used to communicate within IWSNs. Omnidirectional antennas are small, inexpensive, and simple to install, however they have poor spatial reuse, a high collision rate, low energy efficiency, and are susceptible to interference (Curiac *et al.,* 2016). The capacity of wireless networks using Omni-directional antennas is limited due to severe interference and poor spatial reuse. A smart antenna is a directional antenna that can direct its transmitting and receiving capabilities in only one direction (Dai *et al.,* 2013).

When compared to omnidirectional antennas, a smart antenna is highly directional and capable of beamforming, providing benefits such as extended communication ranges, spatial reuse of the spectrum, and reduced interference patterns, enabling higher network performance. Table 3 summarizes the differences between omnidirectional and smart antennas:

Table 3. A brief comparison of smart and omni-directional antennas (Curiac *et al.,* 2016), (Dai *et al.,* 2013).

Characteristics	Omnidirectional Antenna	Smart Antenna
Interference	Lower	Higher
Spatial reuse	Lower	Higher
Transmission range	Lower	Higher
Power requirement	Higher	Higher
Energy efficiency	Lower	Higher
Broadcasting direction	All	Desired
Node orientation	Not required	Required
Price	Lower	Higher
Dimensions	Smaller	Bigger
Transmission security	Lower	Higher
Collision	More	Less

3.4. Interference Mitigation/Rejection Using Smart Antenna

In an area densely populated with sensor nodes and various interference sources, such as is typical in IWSNs. Increasing network capacity for this network is critical. There are two basic ways for increasing capacity, namely Interference reduction/rejection (at the downlink) (at uplink). Thus, to mitigate existing interference, the directed beam can be steered towards the nodes, while rejection of interference is produced by producing nulls/directional beam as the base station receives co-channel user antenna patterns (George and Mary, 2020).

To mitigate interference when using smart antennas in communications, one possible scenario is to first use a DOA algorithm to resolve the angles of arrival of all signals, then separate the Signal Of Interest (SOI) and Signal Not Of Interest (SNOI), and then use the beamformer to direct the maximum radiation of the antenna pattern toward the SOI. Simultaneously, nulls can be placed toward the SNOI. The purpose of adaptive beamforming is to modify the beam by altering the gain and phase on each antenna element to generate a preferred pattern.

The Least Mean Square (LMS) technique, which reduces the Mean Square Error (MSE) iteratively, is one of the most basic beamforming algorithms. The LMS converges to the Wiener-Hopf solution, which is given by $W_{opt} = R^{-1}P$, where R is the input signal's auto-covariance matrix and P is the cross-covariance vector between the desired signal (i.e., SOI) and the input signal. W_{opt} coefficients, while directing the maximum toward the SO1 and the nulls toward the SNOI, do not account for mutual coupling. This issue is addressed by modifying the LMS weights in accordance with W $opt=Z^{-1}$ W_{opt} (Lakshmi and Sivvam, 2017).

3.5. Smart Antenna Prototypes Suitable For IWSN Nodes

Smart antennas must have four basic characteristics to be deployed in IWSN nodes: they must be tiny, economically priced, consume low power, and operate in licensed frequency bands (2.4 GHz Industrial-Scientific-Medical (ISM) band). These constraints severely limit the number of smart antenna construction types that can be used in IWSN sensor nodes (Curiac *et al.,* 2016). Table 4 summarizes the smart antenna prototypes suitable to equip sensor nodes in IWSNs.

Table 4. Smart antenna prototypes for IWSNs operating at 2.4 ghz.

Research	**Antenna's Structure**	**Mote Platform**
Catarinucci *et al.,* 2013.	Radiation structure made of eight microstrip antennas using rectangular two-element patch antenna arrays and a vertical half wave length dipole antenna	STM32W-EXT
Catarinucci *et al,*. 2014.	Four identical antennas, containing two quarter-wavelength L-shaped slot antenna elements, disposed in a symmetrical planar structure	STM32W-EXT
Basikolo *et al.,* 2016.	Reactance Based Uniform Circular Array with four active monopoles distributed on a circular grid.	Tmote Sky
Selavo and Chipara, 2017.	Module has two active monopoles antennas	Tmote Sky
Rodriguez *et al.,* 2017.	SPIDA antenna consisting of a parasitic element(director) and five parasitic elements (reflectors)	Tmote Sky
Dihissou *et al.,* 2018.	Four switchable beam antennas consisting of two fed monopoles and two loaded parasitic monopoles.	Tmote Sky
Varshney *et al.,* 2015.	The antenna has six parasitic elements surrounding a quarter wavelength monopole antenna.	Tmote Sky
Shravan *et al.,* 2019.	2x2 rectangular microstrip patch antenna array with a circular patch	Tmote Sky
Schandy *et al.,* 2019.	Improved SPIDA antenna with multiple (3) directors.	Tmote Sky
Mahdir *et al.,* 2020.	Consists of a monopole antenna as the radiating element and two parasitic patches it.	Tmote Sky

Table 5. Features and benefits of smart antenna in IWSNs

Features	Benefits
1. Signal gain: The process of combining input from many antennas to optimize the available power required to create a given level of coverage.	a. Increased range b. Increased coverage c. Improved link quality d. Increased data rate e. Increase system reliability
2. Interference rejection: Antenna patterns can be generated in the direction of co-channel interference sources to improve the signal-to-interference ratio of the received signal.	b. Interference reduction on the downlink c. Increased capacity d. Precise control of signal nulls e. Frequency reuse reduced distance
3. Spatial diversity: Array's composite information is utilized to reduce fading and other undesired consequences of multipath propagation.	a. Multipath rejection b. Increased bit rates c. Improved spectral efficiency d. Higher reception sensitivity
4. Power efficiency: Combine multiple elements' inputs to maximize downlink processing gain.	a. Reduced expenses - lower amplifier cost. b. Reduced power consumption. c. Higher reliability. d. Reduction in transmitted power e. Increase network lifetime.
5. Security: Reduce the risk of malicious attacks by being immune to attacks launched from outside their narrow radiation domain and relying on node position verification against a trusted node.	a. Prevent eavesdropping. b. Prevent jamming attack c. Prevent wormhole attacks d. Prevent Sybil attacks.
6. Handoff- Splitting of a cell for capacity increase.	a. Reduction in handoff b. Improved system reliability c. Increased capacity d. Enhanced throughput

Although research into developing smart antennas for

IWSN nodes is still in its early stages, the findings produced thus far are encouraging. This enables us to envision innovative approaches of wireless communications between sensor nodes that are more capable of mitigating interferences.

3.6. Benefit of Smart Antenna in IWSNS

The features and benefits of a smart antenna that can help combat the wireless reliability challenges of IWSNs are shown in table 5. ((Lakshmi and Sivvam, 2017), (Hogade and Bodhe, 2012).

Sensor nodes equipped with smart antennas are a promising tool to avoid interference and improve security in IWSN.

4. CONCLUSION AND FUTURE WORK

Smart antennas in IWSNs can provide a number of advantages, including reduced interference, better communication range, and increased network capacity. However, smart antennas have intrinsic limitations that limit their wide variety of IWSN applications. In this study, we begin a review of the advantages and disadvantages of utilizing Smart antennas in industrial settings, concentrating on various interference sources and existing standard mitigation strategies. Following that, an outline of smart antenna approaches is provided. This is followed by research into smart antenna prototypes for industrial applications. Finally, we discuss the benefits and limitations of using smart antennas in IWSNs.

Future work will examine the performance of a smart antenna enabled wireless sensor node in an industrial wireless sensor network scenario in order to overcome the majority of the wireless problems mentioned.

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