Enhancing Industrial 4.0 Connectivity: A D2D-Based Algorithm for Blind Spot Mitigation in 5G Future Networks Enabled Smart Industry

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***Abstract*—The Industry 4.0 is characterized by the integration of advanced and emerging technologies such as Fifth Generation (5G) and Next-Generation Networks & beyond, Artificial Intelligence (AI), Internet-of-Things (IoT), Machine Learning (ML), Robotics, Automation, Blockchain, Cloud Computing, Edge Computing, Augmented Reality (AR), Virtual Reality (VR) and many others. Despite the widespread adoption of 5G, Wireless Fidelity (Wi-Fi) routers, and other wireless technologies in the industry, there are still areas with limited or no coverage, commonly known as blind spots or coverage holes. The Device-to-Device (D2D) communication enables direct communication without a central entity, known as a coordinator or base station. By leveraging D2D communication, IoT nodes can serve as relays to deal with blind spots. In this research, we propose a novel D2D communication-based algorithm to cope with the challenge of blind spots in IoT-based smart industries. The algorithm focuses on nodes situated in blind spots by establishing connections to the network through nearby IoT nodes that function as relays. We demonstrate through simulations that our approach can effectively remove blind spots, improve coverage, increase throughput, and enhance overall system efficiency.**

***Index Terms*—Industry 4.0; IoT; D2D; 5G; Blind Spots; Relay Devices; Smart Industry**

I. Introduction

Industry 4.0, also referred to as the fourth industrial revolution, encompasses the integration of cutting-edge technologies into industrial production processes. It refers to the ongoing automation and digitization of manufacturing and other industrial sectors, using technologies such as the IoT, D2D communication, robotics, AI, cloud computing, cyber security, and big data. Industry 4.0 aims to create ”smart industries” that can operate autonomously with minimal human intervention and can respond to changes in market demand quickly and flexibly. It has the potential to improve efficiency, productivity, and quality, as well as reduce costs and environmental impact [1]. The term ”Industry 4.0” was first introduced in Germany in 2011 as part of a government initiative to promote the digitization of manufacturing. Since then, the concept has gained widespread recognition and has been embraced by industries around the world [2].

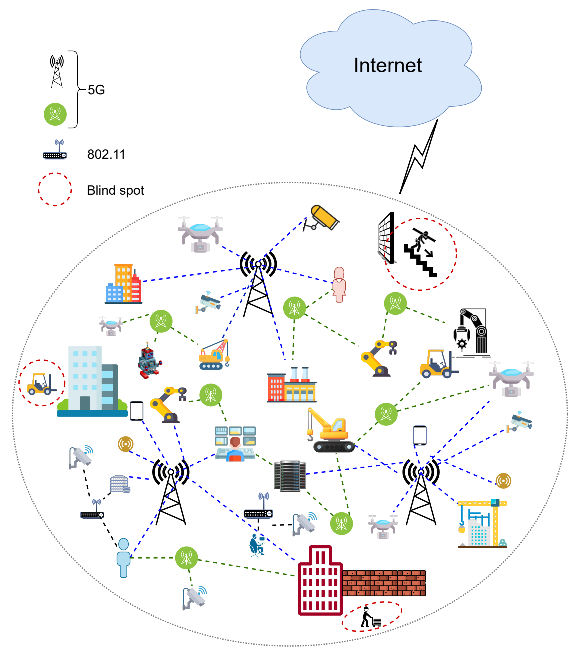

Fig. 1: A typical smart industry scenario with blind spots

Fig. 1 illustrates a common scenario of the smart factory or industrial scenario. We assume that the connectivity between the internet cloud and smart industry is supported by a combination of satellite, 5G, and Wireless Fidelity (WiFi) networks, which are equipped with various types of IoT devices and intelligent machinery. The impact of 5G and IoT on the smart industry has been significant, bringing about a new era of enhanced connectivity and data rates leading to data-driven decision-making. Moreover, the integration of IoT devices with 5G networks have facilitated real-time monitoring and analytics, enabling better predictive maintenance and operational insights [3].

In the context of wireless coverage, blind spots refer to areas or locations where the wireless signal is weak or completely absent. These areas might experience limited or absent network coverage, leading to insufficient connectivity or weak signal quality for devices located within them [4]. Despite the numerous benefits offered by 5G technology, the presence of blind spots within its coverage area can impact the overall network performance. These gaps in coverage can arise from physical obstacles such as buildings or geographical features. The 5G grapples with issues concerning limited penetration and coverage, mainly due to the utilization of millimeter wave (mmWave) and terahertz (THz) frequencies. Network providers must confront these potential areas of inadequate coverage and guarantee dependable service for their customers. Ensuring reliability in coverage involves implementing various strategies, including the deployment of additional small cells, harnessing beam-forming technologies, employing D2D relays to enhance wireless coverage, and applying network optimization methods to boost both coverage and connectivity [5].

In this study, we explore the potential of D2D communication to address coverage limitations within 5G networks, particularly in the context of smart industries. By harnessing D2D communication, devices gain the capability to establish direct connections with one another, even when they are situated in blind spots. This empowers IoT devices to serve as relay nodes, facilitating the transmission of data among themselves until it reaches its intended destination. Consequently, this approach effectively extends network coverage beyond the constraints of traditional 5G infrastructure [6].

Furthermore, this approach offers the potential to alleviate the burden on the 5G network. Devices can communicate directly with each other, eliminating the need for constant data transmission to the cloud or base station. This results in improved data rates, reduced latency, and minimized network congestion [7]. In a smart industry environment that employs IoT technology, various types of IoT nodes can function as D2D relays to mitigate coverage gaps and enhance wireless connectivity [8].

By deploying different types of IoT devices as D2D relays, smart industries can eliminate blind spots and enhance wireless coverage. This enables efficient data collection, and seamless communication between devices, and facilitates the smooth operation of various IoT applications in the industrial environment [9].

The contributions of this paper are outlined as follows:

- We introduce a novel algorithm to cope with blind spots in smart industries utilizing IoT technology.
- Our proposed algorithm leverages D2D communication, enabling nodes lying within the blind spots to establish network connections through nearby IoT nodes acting as relays.
- The simulations conducted in our study demonstrate the effectiveness of our approach in mitigating blind spots, enhancing coverage area, increasing throughput, and improving the overall efficiency of the system.

The rest of the paper is structured as follows; The Sec II presents the state-of-art work. The Sec III presents our proposed system model and results along with a detailed discussion. Lastly, we conclude our work in the Sec V, along with the future direction of this work.

II. Related Work

In [10], an Intelligent D2D communication methodology solves the Multi-Armed Bandit problem using upper confidence bound-based reinforcement learning. The methodology improves energy efficiency for Narrowband IoT (NB-IoT) delay-sensitive applications. In [11], the complexity of caching management in shared storage scenarios for multiple concurrent applications is addressed. It proposes a mathematical framework to model the performance of a shared edge caching system, specifically designed for industry 4.0 and connected car applications. In [12], an energy-efficient relay-assisted technique for IoT-D2D communication is proposed, and optimized to satisfy the energy efficiency requirement. The method introduced in [13] improves spectral efficiency and data secrecy in D2D communication. This is achieved by selecting an appropriate relay node based on the Signal to Interference and Noise Ratio (SINR) and performing an XOR-based decode-and-forward (DF) operation. The work presents in [14], a D2D-enabled collaborative caching at the wireless edge to reduce content delivery latency and improve data acquisition reliability. In [15], joint optimization of resource allocation and probabilistic caching design for D2D communications is explored within a wireless heterogeneous network with Full-Duplex (FD) relays.

III. The System Model

We consider a large manufacturing plant that has thousands of IoT nodes installed throughout the production floor, including sensors on the machines, conveyor belts, and even on the finished products. These nodes collect data ranging from temperature and humidity levels to production rates and quality metrics. In addition to the smart sensor nodes, the plant has a few hundred worker nodes on the production line. These worker nodes are responsible for tasks that cannot be automated, such as quality control, machine maintenance, and manual assembly. The worker nodes in the plant are integrated into the IoT system using wearable smart helmets that track their movements and provide safety alerts if they enter hazardous areas. They are also equipped with devices such as smartphones, tabs, etc. to access real-time data on production rates, quality metrics, and machine status. Fig. 2 displays the floor plan of a smart industry, which consists of different rooms designated for separate operations. The entire production floor is covered with a variety of smart devices including cameras, routers, 5G coverage, IP, and Closed-Circuit Television (CCTV) surveillance devices, and smart sensors such as temperature and humidity sensors.

The light green color represents the 5G coverage, while the pink color represents the WiFi coverage. The mobile worker nodes in the form of cellphones are represented in the Fig.2 with blue and black screens, where the blue screen represents the nodes inside the coverage area, while the black screen represents the nodes in blind spots or coverage holes.

Despite the deployment of routers and other devices, these blind spots pose a significant risk to the mobile worker nodes that frequently pass through these areas. Therefore, in this work, we aim to eliminate these coverage holes using D2D-capable IoT nodes that serve as relays. By leveraging IoT nodes, we can establish links to the network from areas that were previously unreachable, ultimately improving the overall system efficiency, coverage, and throughput.

Let's assume that we have a manufacturing plant with m workers who are equipped with smart helmets that use wireless communication to transmit data to a central server, which monitors worker locations and provides safety alerts. Now one of the workers moves into a blind spot where the wireless coverage is blocked, such as behind a large rack or a moving vehicle. We can model this scenario mathematically using a simple geometric model. we have divided the plant into a grid of square cells, where each cell has a fixed size. We can represent the worker's location at any given time as a point in the grid, with the x and y coordinates indicating the cell in which the worker is located. We represent the location of the large rack or moving vehicle as a set of rectangular cells where the wireless communications are blocked. For example, if the rack or vehicle covers a rectangular area having coordinates of opposite corners (x_1, y_1) and (x_2, y_2), we can represent the area as a set of blocked cells:

$$blocked\_cells = \{(x, y) | x_1 \leq x \leq x_2, y_1 \leq y \leq y_2\}, \quad (1)$$

Now, if the worker's location is within the set of blocked cells, the smart helmet may not be able to transmit data to the central server, and the worker may not receive safety alerts. We can call the blocked cell a blind spot and develop an algorithm that uses IoT nodes as relays to eliminate these blind spots.

A. Proposed D2D-enabled blind spot removing algorithm

In this algorithm, the worker node identifies any nearby IoT nodes and checks if they are capable of relaying worker data. If there are no candidate relays, it waits and periodically rechecks for available relays. If there are candidate relays, it selects the nearest one and attempts to establish a connection. If the connection cannot be established, it waits and periodically retries. Once the worker node exits the blind spot, it resumes normal operation.

Algorithm 1: Proposed D2D-enabled blind spot removal algorithm

```
Input  : Initialize the set of IoT nodes (I) and worker
         nodes (C)
Output: Remove blind spots
repeat
    Worker node c falls into a blind spot;
    c discovers its surroundings and identifies any IoT
      nodes in range;
    for each IoT node i in range do
        Check if i is capable of relaying worker data;
        if yes then
            Add i to a list of candidate relays (R);
    if there are no candidate relays in range then
        repeat
            Relay discovery
        until Until a suitable relay is discovered;
    else
        Select the nearest candidate relay (r) and
          request to establish a connection;
        if r accepts the request then
            Transfer the connection from c to r
        else
            repeat
                Relay discovery
            until Until a suitable relay is discovered;
until worker node c exits the blind spot and resumes
  normal operation;
```

B. IoT Relay Selection Scheme

To generate a relay selection matrix for worker nodes, which are mobile devices scanning for suitable IoT nodes to relay their network connectivity, you need to consider several factors such as signal strength, load on the relay, and battery status of the relay. Here's a detailed explanation of the process:

1) Scanning the Surroundings: The worker nodes, acting as mobile devices, start by scanning their surroundings for potential IoT nodes that can act as relays. They use wireless scanning techniques, such as Wi-Fi or Bluetooth, to detect and identify nearby IoT nodes. Let's consider:

- N: The total number of potential relay nodes
- i: Index variable representing each relay node, where $1 \leq i \leq N$
- $S(i)$: Signal strength of relay node i
- $L(i)$: Load on relay node i
- $B(i)$: Battery status of relay node i

2) Signal Strength Evaluation: Each detected IoT node is assessed based on the wireless signal strength. The signal strength indicates the quality of the connection between the worker node and the potential relay node. The worker node performs the signal strength evaluation based on the received signal strength indicator (RSSI) in which $S(i)$ represents the signal strength of relay node i. It is measured in decibels (dB).

3) Load Evaluation: The worker node evaluates the load or current traffic on each potential relay node, here $L(i)$ represents the load on relay node i. It is measured as a ratio between the current traffic load and the maximum capacity of the relay node. This information helps the worker node estimate the capacity of the relay node to handle additional traffic.

4) Battery Status Evaluation: The worker node also considers the battery status of each potential relay node here $B(i)$ represents the battery status of relay node i. It aims to select a relay node with sufficient battery power to maintain a stable and reliable connection. The battery status is determined by considering factors like remaining charge percentage and the

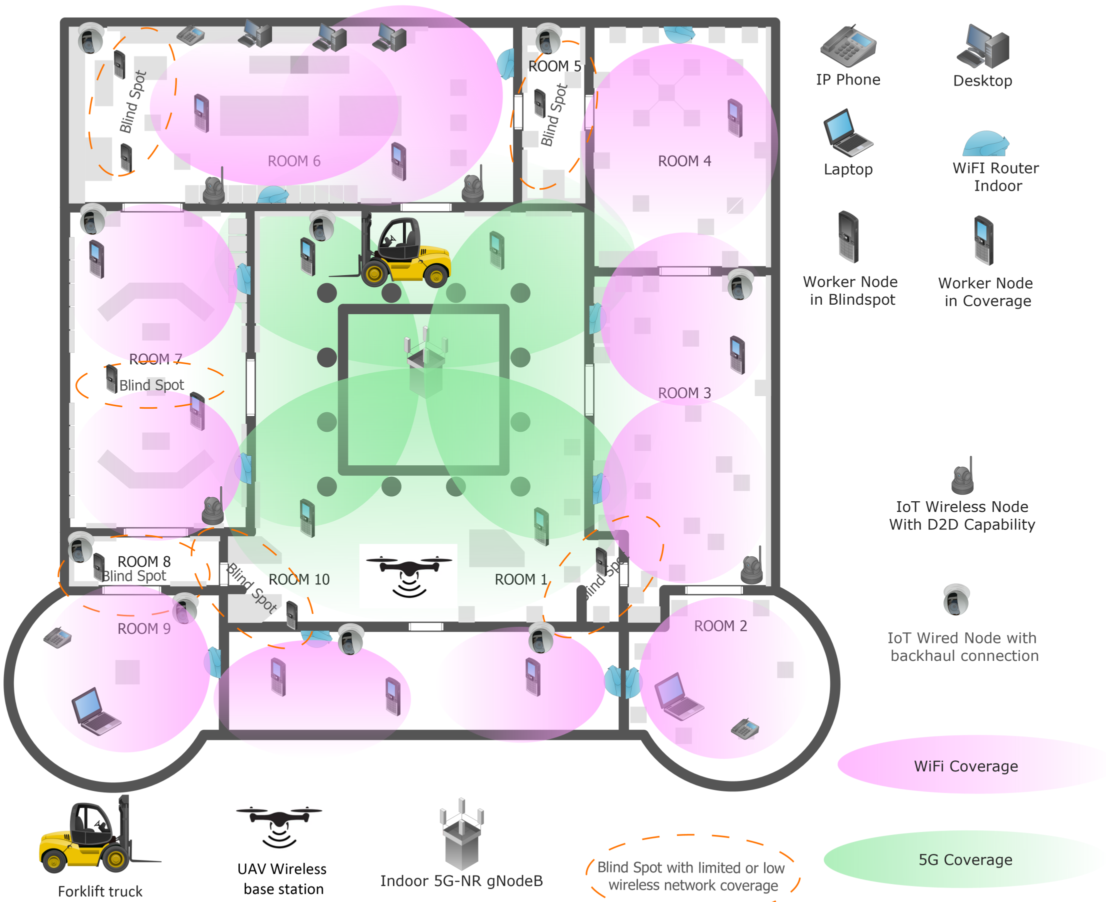

Fig. 2: Floor plan of 5G-WiFi enabled smart industry, illustrating worker nodes, IoT nodes, coverage area, and blind spots.

battery health, or expected battery life based on historical usage patterns. This parameter is specifically added to manage the load on Unmanned Aerial Vehicle (UAV) relays.

5) Relay Selection Criteria: Based on the evaluations performed in steps 2-4, the worker node establishes criteria for selecting suitable relay nodes. The relay selection criteria is defined based on the threshold values or weights for each evaluation metric. Let's denote them as:

- S_{thresh}: Threshold for signal strength (-70 dB)
- L_{thresh}: Threshold for load (0.8)
- B_{thresh}: Threshold for battery status (30%)

Alternatively, we can assign weights to each evaluation metric to reflect their importance:

- S_{weight}: Weight for signal strength
- L_{weight}: Weight for load
- B_{weight}: Weight for battery status

6) Relay Selection Matrix: The relay selection matrix is a tabular representation that lists the potential relay nodes along with their corresponding evaluation metrics. The matrix provides a systematic view of the available relay nodes and their suitability for relaying the worker node's network connectivity. The columns of the matrix may include fields such as the IoT node's identifier, signal strength, load, and battery status.

Relay Node	Signal Strength (S)	Load (L)	Battery Status (B)
1	$S(1)$	$L(1)$	$B(1)$
2	$S(2)$	$L(2)$	$B(2)$
...	...	...	...
N	$S(N)$	$L(N)$	$B(N)$

7) Evaluation and Selection: Using the relay selection matrix, the worker node can compare and analyze the potential relay nodes based on the defined criteria. The worker node selects the most suitable relay node(s) based on these evaluations. It can either choose a single relay node or employ a weighted selection approach considering multiple relay nodes. It can be done using a mathematical formula:

$$\begin{aligned}\text{RelayScore}(i) &= S_{\text{weight}} \cdot (S(i) - S_{\text{thresh}}) \\ &+ L_{\text{weight}} \cdot (L_{\text{thresh}} - L(i)) + B_{\text{weight}} \cdot (B(i) - B_{\text{thresh}}) \quad (2)\end{aligned}$$

The relay node(s) with the highest $\text{RelayScore}(i)$ is selected as the most suitable relay node(s). If multiple relay nodes have the same highest score, tie-breaking mechanisms can be employed (e.g., selecting the one with the highest signal strength).

By following this process, the worker nodes can make informed decisions on selecting suitable relay nodes based on signal strength, load on the relay, and battery status. This allows for efficient utilization of resources and optimal network connectivity in a dynamic environment.

IV. Simulation and Results

In this simulation study, we begin by defining the coverage area of a smart industry, which includes several blind spots within its boundaries. The region is equipped with both IoT and mobile worker nodes, and the system operates efficiently with 100% when all nodes are connected to the network. System efficiency is the optimal utilization of resources to achieve desired outcomes while minimizing waste and maximizing performance. However, when a worker node enters a blind spot, the system's efficiency decreases accordingly, and a safety alert is generated based on the worker's location. The Fig. 3 illustrates the system's efficiency over 1000 time steps, demonstrating that the efficiency is at its highest when all nodes are connected and active. However, when any node enters a blind spot, the system's efficiency decreases. This graph highlights the impact of blind spots on system efficiency, particularly in critical situations such as production lines where maximum efficiency is required and nodes are mobile.

The Table I shows the simulation parameters and their values used in this work.

TABLE I: Simulation Parameters

Simulation Parameter	Values
IoT Nodes	$100 \sim 1000$
Worker Nodes	$20 \sim 100$
Coverage Area	$100 \sim 1000m$
Blind Spots	$10 \sim 50m$
Transmit Power (IoT)	$5mW$
Transmit Power (Worker)	$100mW$
Antenna Gain	$1dB$
Noise Power Density	$-174dBm/Hz$
Bandwidth	$1e6Hz$
Data Rate	$100Kbps$
Path loss (IoT)	$10dB$
Path loss (Worker)	$2dB$

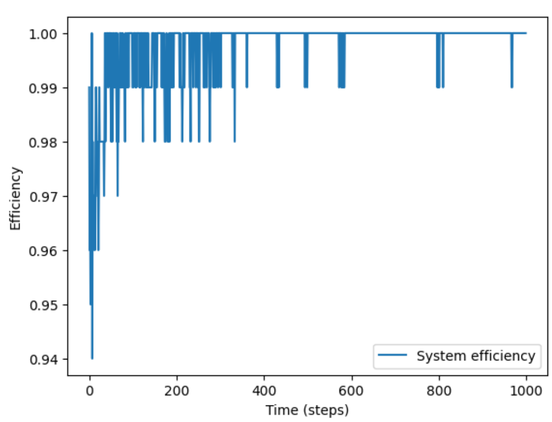

Fig. 3: The effect of blind spots on the system efficiency of IoT network.

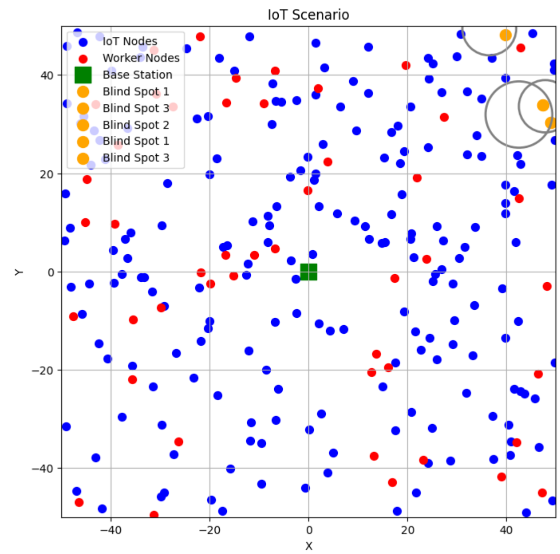

Fig. 4: Simulation environment containing IoT nodes and a worker node in the blind spot

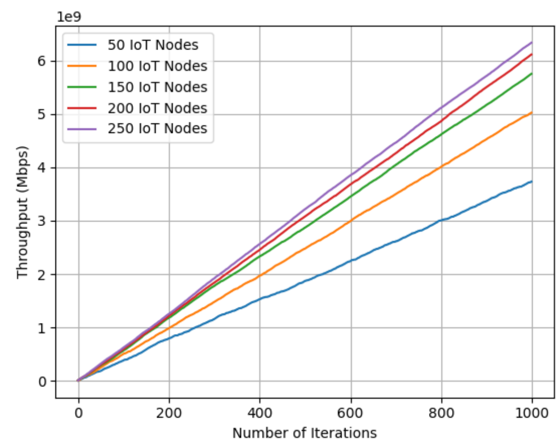

Fig. 5: Throughput of the system for different values of IoT nodes for upto 1000 iterations.

The simulation presented in this work depicts an IoT scenario (shown in Figure 4). In this simulation, the green marker represents the base station located at the center of the area. The blue markers indicate the deployment of IoT nodes throughout the region, and the red marker represents a worker node that moves randomly within the same area.

The worker node has the potential to fall into blind spots, depicted in yellow, where it loses connection to the IoT network. To address this issue, we have implemented our proposed algorithm. The worker node actively searches for candidate relay nodes within its communication range to establish a connection to the network and overcome the blind spot issue. By utilizing this algorithm, the worker node can efficiently connect to available relays and ensure uninterrupted communication with the IoT network.

The Fig. 5 depicts the impact of augmenting the quantity of

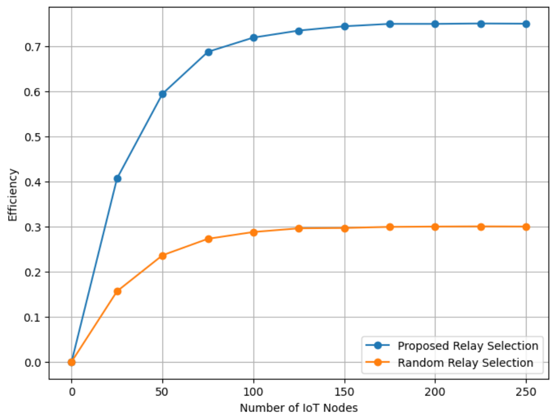

Fig. 6: System efficiency with proposed relay selection algorithm and its comparison with random relay selection algorithm for different values of IoT nodes.

IoT nodes and opting for relays with superior signal potency. The worker node's selection of a relay node with an improved signal strength leads to an augmented throughput of the system. Analogously, the presence of a greater number of IoT nodes in the system increases the likelihood of worker nodes acquiring relays with better signal strengths, thereby resulting in an ameliorated throughput of the system. To elaborate, the diagram illustrates that as the quantity of IoT nodes is increased, the number of relays also increases. Consequently, the worker nodes have a higher likelihood of selecting relays with superior signal strengths, which ultimately leads to higher system throughput. Furthermore, when the worker nodes choose relays with better signal strengths, the amount of data transmitted by the worker nodes increases, resulting in an improved throughput of the system.

The system efficiency, represented in the Fig. 6, indicates the percentage of time the worker node stays connected to a relay node during the simulation. A higher efficiency value signifies the better performance of the proposed algorithm as compared to random relay selection algorithm, ensuring stable connections for the worker node and reducing time spent in blind spots. The results demonstrate that efficiency improves with a higher number of IoT nodes, as more relays become available for worker nodes.

V. Conclusion

In our research paper, we have focused on IoT-based smart industries and proposed an algorithm to overcome the problem of blind spots. We demonstrated that nodes falling into blind spots can utilize D2D communication to establish a link to the network using IoT nodes. To fortify our proposition, we have carefully developed a sophisticated mathematical model to determine the equations of energy consumption. Additionally, we conducted simulations to validate our approach. The results of our study indicate that the proposed method can help remove blind spots leading to improved coverage, throughput, and overall system efficiency. This research work holds significant potential for enhancing the future of IoT-based smart industries by ensuring reliable communication and improving worker safety.

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