ISSN 2712-0554
Original Research

Heritage and Sustainable Development
Vol. 6, No. 1, March 2024, pp.111-126
https://doi.org/10.37868/hsd.v4i1.389

Sustainable optimizing WMN performance through meta-heuristic TDMA link scheduling and routing

Haider Rasheed Abdulshaheed[1*], Harshavardhan Reddy Penubadi[2], Ravi Sekhar[2*], J. F. Tawfeq [3], Azmi Shawkat Abdulbaq[4], A. D. Radhi[5], Pritesh Shah[2], H. M. Gheni[7], Ritesh Khatwani[8], Neena Nanda[9], Pradip Kumar Mitra[9], Shubhra Aanand[10], Yitong Niu[11]

[1] Computer Engineering Techniques Department, Baghdad College of Economic Sciences University, Iraq
[2] Symbiosis Institute of Technology (SIT) Pune Campus, Symbiosis International (Deemed University), India
[3] Department of Medical Instrumentation Technical Engineering, Medical Technical College, Al-Farahidi University, Iraq
[4] Renewable Energy Research Center, University of Anbar, Iraq
[5] College of Pharmacy, University of Al-Ameed, Iraq
[7] Computer Techniques Engineering Department, Al-Mustaqbal University College, Iraq
[8] Symbiosis Institute of Business Management, Pune, Symbiosis International (Deemed University), India
[9] Vivekanand Education Society's Institute of Management Studies & Research, India
[10] Balaji Institute of International Business, Sri Balaji University Pune, India
[11] School of Aeronautical Engineering, Anyang University, China

*Corresponding author E-mail: ravi.sekhar@sitpune.edu.in

Received Jan. 21, 2024
Revised Feb. 28, 2024
Accepted Mar. 6, 2024

Abstract

Wireless mesh networks (WMNs) have become a popular solution for expanding internet service and communication in both urban and rural areas. However, the performance of WMNs depends on generating optimized time-division multiple access (TDMA) schedules, which distribute time into a list of slots called superframes. This study proposes novel meta-heuristic algorithms to generate TDMA link schedules in WMNs using two different interference/constraint models: multi-transmit-receive (MTR) and full-duplex (FD). The objectives of this study are to optimize the TDMA frame for packet transmission, satisfy the constraints, and minimize the end-to-end delay. The significant contributions of this study are: (1) proposing effective and efficient heuristic solutions to solve the NP-complete problem of generating optimal TDMA link schedules in WMNs; (2) investigating the new FD interference model to improve the network capacity above the physical layer. To achieve these objectives and contributions, the study uses two popular meta-heuristics, the artificial bee colony (ABC) and/or genetic algorithm (GA), to solve the known NP-complete problems of joint scheduling, power control, and rate control. The results of this study show that the proposed algorithms can generate optimized TDMA link schedules for both MTR and FD models. The joint routing and scheduling approach further minimizes end-to-end delay while maintaining the schedule's minimum length and/or maximum capacity. The proposed solution outperforms the existing solutions in terms of the number of active links, end-to-end delay, and network capacity. The research aims to improve the efficiency and effectiveness of WMNs in most applications that require high throughput and fast response time.

Keywords: Computer science, Sustainable, Wireless mesh networks, TDMA, Meta-heuristic algorithms, Optimization, End-to-end delay

1. Introduction

A wireless mesh network (WMN) is a kind of wireless network that uses mesh routers and clients. Mesh routers are linked to the Internet. On the other hand, mesh clients include users who use this network system. The link routers talk with each other to give network connections for the mesh clients [1]. Women are important because they can access the internet and talk to all city life parts, as well as country places where normal wired networks don't work or cost too much. WMNs are different because they can control themselves, make their own decisions, and fix problems. This makes them stronger than regular wireless networks that don't have these abilities. WMNs are a kind of wireless network with mesh routers and mesh clients [2]. They are important because they can give internet service and talk to all city life stuff as well as countryside places, where old wired networks don't work well or cost too much. Ladies are also known for their ability to control themselves, come together by choice, and fix problems. This makes them more strong and trustworthy than old-fashioned wireless networks [3]. But, making the best TDMA plan for WMN is a known difficult problem called NP-complete. This means it's too hard to solve when the network size gets big. So, heuristic ways are used to make almost perfect schedules. The suggested answer uses the new artificial bee colony (ABC) heuristic method and/or widely used methods like genetic algorithm (GA). These are designed to solve every model's problem [4]. We will compare the new methods with what is already known to show they work well and are fast. The suggested answer also uses shared routing and scheduling to further cut down delay. You can find the average wait time by adding up all the shortest paths from one node to another in a graph using an algorithm like Dijkstra. It only finds the fastest route but doesn't take delay into account. Then, it counts the overall time wished for each shortest route by using a wonderful body desk. Then, take the solution and proportion it between all the hyperlinks. It's key to apprehend that taking the fastest course doesn't constantly result in the least ready time from start until finish. A nicely planned TDMA agenda could make the community paintings higher, shorten wait instances, and deliver enjoyment to human beings. The advised plan with meta-heuristic ways can create schedules near best. These plans are measured in opposition to different recognized algorithms to expose that they paint well and quickly. The blended manner of routing and scheduling can also cut down ready time more, making the community work better [5].

This research aims to provide novel meta-heuristic algorithms to generate time-division multiple access (TDMA) link schedules in wireless mesh networks that use specific interference/constraint fashions: (i) multi-send-receive (MSR) and (ii) two-way sending at the same time or full-duplex (FD). The made plan for every requirement tries to lower top-notch body size, get the most active connections, and/or lower wait time from beginning to completion. Moreover, they take a look at an even cognizance of collective setup and timing for each fashion to similarly reduce the total wait time. This may be finished with the aid of locating better paths while retaining schedules shortest or highest potential viable [6]. They may even examine shared-making plans, electricity control, and speed control troubles for both MTR and FD fashions. The issues noted in advance are called NP-complete. So, this concept will consciousness the use of two famous strategies known as the artificial bee colony (ABC) and genetic algorithm (GA). In specific, the concept has 4 important dreams:

(a) To design an efficient and novel ABC and/or GA solution to generate the TDMA schedule for MTR that minimizes superframe length, maximizes network capacity, and/or minimizes network end-to-end delay.

(b) To design an efficient and novel ABC and/or GA solution to generate the TDMA schedule for FD that minimizes superframe length, maximizes network capacity, and/or minimizes network end-to-end delay.

(c) To design an efficient and novel ABC and/or GA solutions to solve the joint routing and scheduling for goals 1) and 2) to generate a better set of paths, not necessarily the shortest paths, and TDMA schedule that can further reduce the end-to-end delay.

(d) To design an efficient and novel ABC and/or GA solutions for improving scheduling optimization, power control, and rate control in MTR and FD models.

2. Background

2.1. Wireless mesh networks

The WMNs have been used in many applications such as broadband Internet access, indoor WLAN coverage, transportation systems, security surveillance systems, and health and medical systems [7]. As shown in Figure 1, WMN includes mesh routers (MRs), mesh clients (MCs), as well as gateways (GWs) as portals to access the Internet [8,9]. MRs are usually less mobile as compared to MCs, and the WMNs can integrate with other different networks by using GWs as bridging functions. The MCs may be mobile or stationary, and they can make mesh networks with mesh routers as well as with themselves. Each router in WMN can be equipped with different types of antennas such as omni-antenna, or smart-antenna that result in different WMN communication models such as (i) multi-transmit-receive (MTR), and (ii) full-duplex WMN [10]. WMNs are characterized by some specifications such as multi-hop, mobility, and multiple radios, as well as their capabilities of self-regulation, self-forming, and self-healing. This study considers the multi-hop, single-channel radio and static backbone routers equipped with smart antennas for both WMN communication models. Such models can be used among others in the rural area that lacks communication infrastructures [11]. For multi-hop WMN, carrier sense multiple access with collision avoidance (CSMA-CA) protocol is inappropriate way due to hidden node problems and exposed terminal problems [12]. In contrast, the time-division multiple access (TDMA) scheduling can offer spatial reuse and thus is suitable for this type of network [13,14].

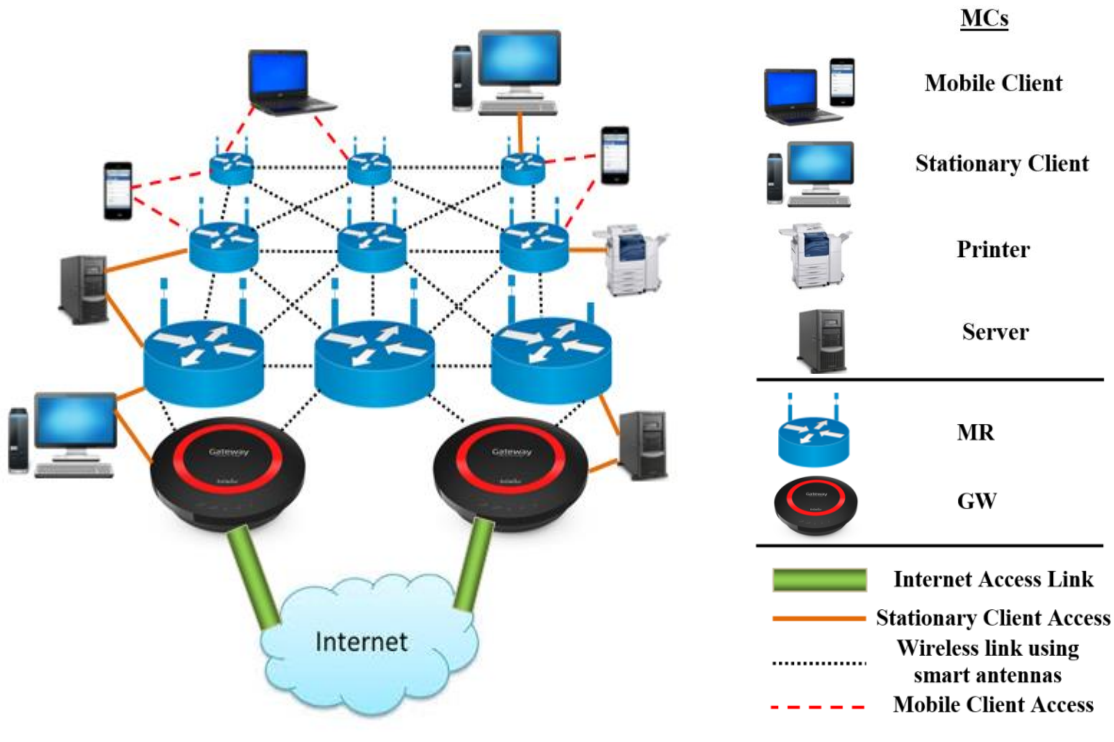


Figure 1. WMN infrastructure overview

In TDMA, the transferred data is separated into frames, and frames are separated into time slots. A set of nodes can transmit at the same time slot when they do not interfere with each other, and thus TDMA allows WMN with a single channel to support multiple transmissions in a conflict-free manner [15]. The main purpose of TDMA link scheduling in WMN is to maximize the capacity of WMN and minimize end-to-end delay [16]. The capacity can be increased by minimizing the length of the superframe as well as maximizing the link activations in each time slot. Note that each TDMA schedule must provide each node with at least one or more transmission opportunities to satisfy the given network load. This project aims to design novel solutions to produce such an effective TDMA schedule. Table 1 shows the related work comparison with the weaknesses, contributions, and parameters.

Table 1. Related work comparison: weaknesses, contributions, and parameters

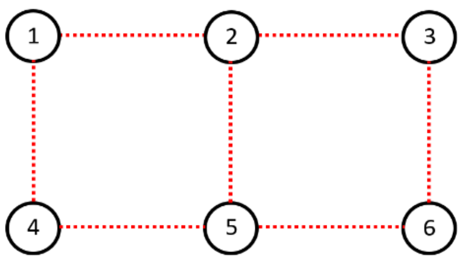
Related Work	Weakness	Contribution	Utilized Parameters
Study [17]	High computational complexity	Proposed a heuristic algorithm optimizing link scheduling	Network topology, traffic demands
Study [18]	Lack of consideration for dynamic environments	Introduced a dynamic power control mechanism for adaptive transmission rates	Signal-to-noise ratio (SNR), channel conditions
Study [19]	Limited scalability for large networks	Developed a distributed algorithm for relay node power assignment	Network size, routing tree structure
Study [20]	Ignored interference effects	Proposed an interference-aware scheduling algorithm	Interference models, transmission power levels
Study [21]	Narrow scope on specific network conditions	Introduced a generic framework adaptable to diverse WMN configurations	Variable parameters, network heterogeneity

The table offers a comprehensive overview and comparison of various studies within the field, highlighting their strengths and weaknesses, contributions to the domain, and the parameters utilized within their research frameworks. Every entry gives us information about the problems or limits of those studies. These might include computing complications, narrow-range issues, or restrictions in certain web connection conditions. At the same time, it highlights their major achievements. These include creating problem-solving algorithms to adjust dynamically and coming up with big solutions that can be shared by many people. The table shows what each study used. It also shows that people doing the research depend on many things like how networks are set up, traffic needs, signal strength compared to noise levels, and interference models plus the size of the network. This comparison helps us to see the different ways studies are done. It shows their unique parts and where they focus in the study field.

2.2. WMN network model and notation

Think about a picture G = (V, E) where V has some circles for routers and E are lines connecting those circles in a WMN. Figure 2 illustrates an example WMN with $|V| = n$ and $|E| = m$. Let $v_i \in V$ represent router i equipped with smart antennas capable of forming up to $b_i \geq 1$ links, where b_i denotes the number of links or interfaces on vertex i [22]. In other words, router v_i has the capacity to transmit to or receive from b_i neighbors simultaneously. Let N_i symbolize a set containing v_i 's neighbors, and $e_{ij} \in E$ represents a directional link (antenna) from router i to j. We assume each v_i has an equal degree related to the number of in and out-links. Additionally, all links share a single channel. It's important to note that any router can or cannot transmit to or receive from one or more routers simultaneously, depending on the interference models discussed in the following sections. Moreover, we assume all nodes are fixed or static.

Maximizing network capacity and minimizing end-to-end delay are the primary objectives of the link scheduling problem in WMNs. Thus, verifying the maximum number of activated links in a time slot is crucial to achieving these objectives. Figure 2 illustrates an example of a WMN grid topology consisting of six nodes and seven links, where each node is capable of forming up to $b_i = 3$ links [23]. Let S represent a TDMA superframe schedule comprising a set of time slots (t), sufficient for data packet transmission. Each time slot contains an $|E|$-dimensional activation vector e_{ij}, where each element corresponds to a link (i, j).



(a) Grid topology with 6 nodes and 7 links

Slot1	Slot2	Slot3	Slot4	Slot5	Slot6
e_{12}	e_{21}	e_{32}	e_{41}	e_{52}	e_{63}
e_{14}	e_{23}	e_{36}	e_{45}	e_{54}	e_{65}
	e_{25}			e_{56}	

(b) TDMA schedule

Figure 2. An example of WMN topology and its possible TDMA schedule

The superframe length denotes the count of necessary time slots to activate every link within the WMN at least once. Determining the network capacity involves computing the total number of time slots divided by the activated links within a superframe. To calculate the average end-to-end delay, we first sum the shortest path for all nodes in the graph. This computation relies on algorithms like Dijkstra's algorithm, which identifies the shortest path in a router without factoring in delay. Subsequently, we calculate the total required time slots to fulfill each end-to-end shortest path based on the superframe table. Dividing this result by the total number of links provides an average. However, it's crucial to note that relying solely on the shortest path doesn't always yield the shortest end-to-end delay [24].

2.3. Multi-transmit-receive (MTR) network

The TDMA schedule primarily aims to activate the maximum number of links within each time slot while striving to reduce the superframe size based on conflict-free principles. Some experts suggest giving routers powerful, smart antennas that allow for MTR communication. This follows the mix-tx-rx rule which stops nodes from sending or receiving at once. Many new ways to improve network performance have been proposed: algorithms like Algo 1 and others using approximation methods or finding sets of alternatives affect how connections are turned on schedule These tactics use algorithms linked to biggest cut issues, shared routing, and scheduling. They also change the order time slots happen. Some ideas purpose to apply shortcut strategies like Max-Degree-First (MDF) and Heavy-Weight-First (HWF). These assist in efficaciously dealing with scheduling problems discovered in the MTR wireless metropolitan network. In the attempt to make MTR WMNs higher, work makes a specialty of shortening superframe lengths, getting more common link uses and less ready time from one end to some other. These efforts take a look at one-of-a-kind ways, like the usage of optimization strategies which include ABC and GA to find a nice TDMA timetable that meets these regulations. In WMNs, creating a timetable for sending information with the shortest superframe time could be very critical. It aims to increase how a whole lot of stuff can move over the community and reduce delays from quit to stop, which has been shown in extraordinary studies. For instance, one study deals with a way to write down the policies for the usage of MTR networks. It makes a specialty of running out whilst every hyperlink must ship or get hold of statistics so that enough records can be transmitted across all of them. Other studies inspect how TDMA technology can permit extraordinary ships and get hold of actions in WMNs at the same time. They want to create schedules that limit end-to-end delays while increasing network capacity too. Talks about making WMNs more efficient also happen. They assume TDMA plans, control how much power is used, and adjust the rate based on signal-to-interference-and-noise levels (SINR) for better transmission speeds. Studies have shown that raising the highest sending power can affect how energy capacity is balanced, possibly increasing network ability without spending more on energy. Additionally, studies look at spatial reuse time-division multiple access (STDMA) ideas. These use the same methods of controlling power and adapting speed based on SINR for optimization as before. Extra work focuses on choosing the right power for relay points and figuring out the best times to send packets. This helps reduce all packet wait time within a certain map of routes given. Proposals offer different ways to start links. They bring the best possible connected groups from general layouts, giving various spends of time and high quality [25-26].

2.3.1. Full-duplex network

The creation of self-cancellation methods has brought a big idea in wireless systems called full-duplex (FD). This concept allows you to speak and listen on the same line. This plan wants to improve the ability of WMNs by also lowering the normal wait time from one end to another. In the FD model, at once you send and get messages on a single channel which uses it well. The FD model lets nodes send and get at the same time on one channel. It uses extra antennas for each receive antenna to cancel out their interference as well. Consequently, nodes intending to perform simultaneous transmission require three antennas each: one for sending, one for receiving, and an extra antenna to stop self-disruption. This system works differently than the MTR model because it has enough antennas for each node. In perfect situations, all WMN links could be turned on during a one-time slot. However, inadequate antennas may necessitate distributing activated links across time slots based on the available antennas per node. Notably, existing research has proposed algorithms for the full-duplex link scheduling problem (FDLSP) in wireless sensor networks (WSNs). These algorithms include synchronous and asynchronous approaches. Additionally, heuristic algorithms tailored for multiple input multiple output (MIMO) or full-duplex models have been introduced to reduce superframe length. Considering this scenario, utilizing algorithms such as ABC and/or GA is proposed to solve scheduling problems in WMNs within the FD model, as no existing works have explored link scheduling for this specific FD model in WMNs [27-32].

2.4. Meta-heuristics

Meta-heuristics have gained significant traction as highly effective techniques for combinatorial optimization. Their key advantage lies in their capacity to tackle complex problems, even with limited or no prior knowledge about the search space. Consequently, these methods operate efficiently when dealing with large-scale problems. There exist various types of meta-heuristic algorithms, such as particle swarm optimization, ant colony optimization, ABC, and GA, which have been successfully applied in solving scheduling problems. Additionally, meta-heuristics have found application in resolving NP-complete optimization problems, including those related to the traveling salesman and maximum clique. Moreover, these methods have been instrumental in addressing search problems within machine learning domains, notably in tasks like Neural Network Training. The current work is trying to use ABC and/or GA to make a TDMA plan for the mentioned models. These smart algorithms will likely give good answers for scheduling in the given models inside WMNs.

2.5. ABC algorithm

In 2005, Karaboga brought in the ABC method. It's a good and useful way that use ideas from nature to solve problems. ABC has shown its skill in handling math problems, helped train brain networks, and fixed many different optimization issues over time. This can be used in many areas like computer programming, controlling machines, and working with pictures. It's also been helpful for special situations within systems that use wireless sensors. ABC works like a group of smart beings. It has working bees (EBs), and jobless searching for food bees (UFBs) that include search and watcher type ones which are scout (SB) or observer companionship members, all seen as part floating about details when consuming something tasty to enjoy. Worker bees and forager bees work together to find good food sources in the area around their hive. At first, SBs look for different food sources and share the found information with OBs using communication ways linked to hives. Maintaining balanced quantities of OBs, FSs, and EBs within the population ensures their joint efforts remain cohesive. Moreover, EBs transition into SBs if their solutions stagnate after repeated attempts, and their solutions are replaced accordingly. Within the realm of optimization, solutions within the ABC algorithm mirror the number of food sources. Well-positioned food sources represent valuable solutions, while the quantity of nectar within these sources corresponds to the fitness cost of associated solutions [17].

2.6. Genetic algorithm

GA is one of the artificial intelligence research methods that use normal selection and evolution. The algorithm aims to balance between two principles, firstly, *exploitation* (including *selection* and *crossover*) which tends to make convergence on an acceptable but suboptimal solution, and secondly, *exploration* (including *selection* and *mutation*) prevents an early convergent or meeting, noise tolerant, as well as setting up a parallel. Generally, GA uses the following six stages:

(1) To problem in chromosomes: it is not possible to restrict the search area by the observation present system in the chromosome of a different coding scheme, depending on the nature of the actual problem. $C = [C^1, \ldots, C^N]$ is a chromosome, where is permutation vector in integer.

(2) Initialization: $\{C_p = [C_P^1, \ldots, C_P^N]$, p = 1, …, P$\}$ is the population of permutation chromosomes in initial experiments, initialized randomly from 1 to N. Note that P is the population size.

(3) Finding the evaluation of fitness: According to the order of permutation, a slot allocation may be performed by using the greedy algorithm determined such as the following:

Initial value: $C_p = [C_P^1, \ldots, C_P^N]$ and output value: M, ρ

(4) Genetic operators (selection, crossover, mutation): according to the fitness function, in the mentioned equation, three main kinds of genetic operators are required in modifying the population [21].
(5) Replacement: After a predetermined number of children is generated by the genetic operator, the strategy of replacing is needed to modify the new generation old population.
(6) To terminate the process: GA depends on the stopping condition as a constraint to decide whether to stop the research or continue. This strategy not only ensures that there is sufficient time for the GA to converge, processing time as well as over-unavoidable high complexity.

3. Methodology

The significant contributions of the works described in this proposal are as follows:

1) An optimal TDMA links schedule in WMN is crucial. Since the problem is NP-complete, the proposal to design its effective and efficient heuristic solutions is important to solve the problem for large networks.
2) To the best of our knowledge, the new FD interference model has not been investigated to improve the network capacity above the physical layer. So far there is no research work on producing an optimal link schedule for the model.
3) Meta-heuristics have been used for various optimization problems. However, they have not been used in optimizing the link schedule of WMN.

3.1. Goal 1: Multi-transmit-receive network

In the MTR model, interference occurs only when a node transmits and receives simultaneously, meaning a node can either send or receive data from neighboring nodes at a given time. Each node can communicate with one or multiple nodes concurrently. The activation of every link must occur at least once, and any two links within a range of more than one hop can be activated simultaneously. As a premise, in each time slot, only one packet is assumed to be transmitted or received for every activated link. Illustrated in Figure 4, where T = 2 time slots, L = 14 links, and the average link activation per time slot (Lave) is calculated as 14 / 2 = 7.

Slot1	e_{21}	e_{23}	e_{25}	e_{41}	e_{45}	e_{63}	e_{65}
Slot2	e_{12}	e_{14}	e_{32}	e_{36}	e_{52}	e_{54}	e_{56}

Figure 3. Schedule examples of Figure 2 for MTR

Our goal is to create and assess the efficiency and efficacy of our meta-heuristic algorithms in resolving the scheduling dilemma. Here, nodes *i* and *j* are considered adjacent neighbors or merely one hop away. The N × N connectivity matrix C defines the network topology as:

$$c_{ij} = \begin{cases} 1, & \text{if host } i, j \text{ are one} - \text{hop apart} \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

We aim to enhance the TDMA frame for packet transmission while ensuring it complies with the given constraints. This TDMA frame is recurrently utilized over time.

$$f_{ij} = \begin{cases} 1, & \text{if host } i, j \text{ are one} - \text{hop or two} - \text{hop apart} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

An (N × N) binary matrix $X = x_{mj}$, which is defined in Equation 3, is used to represent a TDMA superframe, and the slot number of a TDMA superframe is symbolized by M.

$$x_{mj} = \begin{cases} 1, & \text{if } m\text{th time slot to be assigned to host j} \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

ρ represents the channel utilization for the whole network as illustrated in Equation 4.

$$\rho = \frac{1}{MN} \sum_{m=1}^{M} \sum_{j=1}^{N} x_{mj} \tag{4}$$

Finding a TDMA superframe with the lowest number of slots as well as satisfying all constraints is the main target of the scheduling problem to get maximum channel utilization (ρ). Broadcast scheduling problems are subject to some constraints such as minimizing M and maximizing ρ.

$$\sum_{m=1}^{M} x_{mj} \geq 1, \quad \forall j \tag{5}$$

$$\sum_{m=1}^{M}\sum_{i=1}^{N}\sum_{j=1}^{N} x_{mi}x_{mj} f_{ij} = 0, \tag{6}$$

No-transmission constraint is represented in Equation 5, while the no-conflict constraint is represented in Equation 6.

3.2. Goal 2: Full-duplex network

In this section, we model a single-channel full-duplex WMN. Let d_v be the degree or number of neighbors of node v, and each node v has Δv antennas that can be used for either transmission or reception. To enable full-duplex mode, each node must dedicate one transmit antenna to null self-interference each receive antenna. For example, node 1 in the previous grid topology in Figure 2 must have at least Δ(node 1) = 2 + 2 * 2 antennas so that it can transmit to and receive from its d_{node1} = 2 neighbors in full-duplex at the same time. While node 2 must have at least Δ(node 2) = 3 + 2 * 3 antennas so that it can transmit to and receive from its d_{node2} = 3 neighbors in full-duplex at the same time. In general, each node v is able to handle at most m_v transmitting streams and n_v receiving streams, if it has at least $\Delta v = m_v+2n_v$ antennas. We call this constraint a Min-Antenna (MA) constraint.

Slot1	e_{12}	e_{14}	e_{32}	e_{36}	e_{54}	e_{56}
Slot2	e_{21}	e_{23}	e_{41}	e_{45}	e_{63}	e_{65}
Slot3	e_{52}	e_{54}	e_{32}	e_{36}	e_{14}	
Slot4	e_{25}	e_{21}	e_{41}	e_{45}	e_{63}	

1→ 2
1 → 2 → 3
1 → 4
1 → 2 → 5
1 → 2 → 3 → 6

Figure 4. (a) Schedule examples of Figure 2 for FD (b) The shortest path from node 1 to others

As shown in Figure 4(a), the length of the superframe in this example is longer than the superframe in the MTR model because we use the minimum number of antennas, i.e. Δv = 2 for each node $v \in V$, to generate the TDMA schedule such that (i) each link $e \in E$ is activated at least once subject to satisfying the MA constraint; (ii) the superframe length (T) of the TDMA is minimized; and (iii) the average number of link activations (L) in the TDMA is maximized; we define the average link activations, $L_{ave} = L / T$. Note that in any time slot, any link cannot be activated more than once. As shown in Figure 4(a), T = 4, L = 22, and L_{ave} = 22 / 4 = 5.5. It is important to develop a more effective heuristic algorithm to find the optimal solution or approximate solution of the optimal solution in polynomial time. Mathematically, the ABC approach can be described as follows.

Initialization phase: scout bees haphazardly generate the population, which is FSs. An input vector to the optimization problem x_m will control each food source (FS), there are D variables in x_m and D represents the dimension for the search space of the objective function to be improved. Randomly, Equation 1 produces the initial FSs.

$$\boldsymbol{x_m = l_i + rand\,(0,1) * (u_i - l_i)} \ \ldots\ldots\ldots \tag{1}$$

The lower and upper bounds for solution space of objective function can be represented by l_i and u_i respectively. While, the rand (0, 1) equation creates a number, which is generated randomly, in range between 0 and 1.

Employed bee phase: new FSs are discovered by EBs within the neighborhood of the current FS. EBs will memorize information about the FSs that have a higher quantity. Onlooker bees will receive this information inside the hive. Equation 2 will determine and calculate v_{mi} which is a neighbor FS [8].

$$\boldsymbol{v_{mi} = x_{mi} + \emptyset_{mi}(x_{mi} - x_{ki})} \ \ldots\ldots.. \tag{2}$$

While it is important to know that *i* is a randomly selected parameter index, x_k is an FS which is also randomly selected, and ϕ_m represents a random number in the range between -1 and 1. The level of this parameter is defined as an appropriate adjustment on specific issues. The fitness of FSs is necessary to get the global optimal. Calculating the fitness is done by Equation 3, and then applying a greedy selection between x_m and v_m.

$$\boldsymbol{fit_m\,(x_m)} = \begin{pmatrix} \frac{1}{1+f_m\,(x_m)},\, f_m\,(x_m)>0 \\ 1+|f_m(x_m)|,\, f_m\,(x_m)<0 \end{pmatrix} \;\ldots\ldots \tag{3}$$

Where $f_{m(x_m)}$ represents the objective function value of x_m.

Onlooker bee phase: The profitability of food will be calculated sources by onlooker bees, observing the waggle dance in the dance zone and thereafter selecting a higher food source randomly. Then, onlooker bees carry out a random search for the food source with their neighbors. Depending on the profitability of all resources the food quantity is evaluated. Where P_m can be specified by Equation 4.

$$\boldsymbol{p_m} = \frac{fit_m(x_m)}{\sum_{m=1}^{SN} fit_m(x_m)} \;\ldots\ldots\ldots\ldots \tag{4}$$

Where the fitness of x_m can represented by $fit_m(x_m)$.

Depending on Equation 5, the neighborhood of the food source is searched by onlooker bees.

$$\boldsymbol{v_{mi} = x_{mi} + \emptyset_{mi}(x_{mi} - x_{ki})} \;\ldots\ldots\ldots\ldots\ldots \tag{5}$$

Scout phase: the scout bee cancels the solutions that have profitability that cannot be enhanced, after exceeding the predetermined number of trials, which is called "limit", and after overriding allocated time. Then, new solutions are searched by scout bees randomly. The new solution x_m will be founded by scout bees using Equation 1 in the initialization phase.

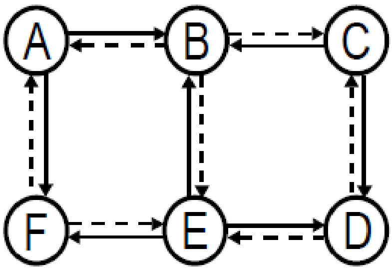
We aim to develop and evaluate the efficiency and effectiveness of our algorithms to solve the problems of scheduling. We intend to use ABC and/ or GA.

3.3. Goal 3: Joint routing and scheduling to minimize end-to-end delay

The required time for sending a packet across WMNs between source and destination nodes is called end-to-end delay or one-way delay. Another important concept that needs illustration is that the best path is not necessarily the shortest path. In other words, the shortest path in some cases takes time to transmit or receive longer than other paths. For example, as shown in Figure 4(b), 1→2→5 represents the shortest path between nodes 1 and 5. The time taken to execute this path will cost 4 time slots depending on the superframe scheduling in Figure 4(a). On the other hand, if we take another path such as 1→4→5, the path will cost just 2 time slots depending on the same superframe scheduling as well. This means using a non-shortest path, sometimes, can produce better end-to-end delay. Therefore, designing efficient and novel ABC and/or GA solutions will solve the joint routing and scheduling to generate a better set of paths, not necessarily the shortest paths, and a TDMA schedule that can further reduce the end-to-end delay.

3.4. Goal 4: Joint scheduling, power control, and rate control

In contemporary communication networks, rate control is pivotal to prevent congestion and ensure equitable access for users. Within multi-hop wireless networks, the capacity of each radio link hinges on signal and interference levels, influenced by power levels and transmission schedules across other links. Consequently, the capacity region adopts a complex form contingent on the resource scheduling within the underlying physical and MAC layers. Mesh routers, typically devoid of energy constraints, exhibit infrequent topology alterations primarily attributed to node failures. Despite this, efficient solutions for link scheduling in MTR and FD within WMNs are still imperative to bolster network capacity and curtail end-to-end delays. Our approach revolves around reducing the number of slots, ensuring each link activates at least once. Drawing from the framework presented in "A Distributed Maximal Link Scheduler for Multi Tx/Rx WMNs," we aim to optimize the TDMA problem by maximizing the active links per slot while minimizing the frame size, thereby minimizing the required number of slots.



Superframe	
slot-1	slot-2
B→A	A→B
B→C	C→B
B→E	E→B
D→C	C→D
D→E	E→D
F→E	E→F
F→A	A→F

Figure 5. Link scheduling in WMNs: Maximizing active links while minimizing frame size

The problem at hand can be formulated as follows:

$$\min \sum_{k=1}^{|\mathcal{B}|} \lambda_k$$

$$\sum_{t=1}^{|\mathcal{B}|} \lambda_t e^t \geq \mathbf{1} \tag{6}$$

To validate our solution, we aim to introduce additional parameters such as toggling options (on/off) and examining inactive links. Our approach involves modifying the slot direction to align with the activity direction, effectively minimizing the slot count. We'll portray the WMN as an enriched directed graph G (V, E), providing additional specifics. In this context, each slot 't' encompasses a |E| dimensional activation vector 'et', where each component corresponds to a link (i, j), marked as one if the link is active in slot 't'. This 'et' vector delineates the links adhering to the no-Tx-Rx constraint. It's crucial to clarify that we denote a transmission set 'et' as maximal when no further links can be added without contravening the specified constraint. The set 'B' comprises all these maximal feasible transmission sets. Additionally, let λt represent a binary variable (λt ∈ {0, 1}), indicating whether the transmission set 'et' is part of the superframe 'S'. Lastly, the vector '1' denotes a |E| dimensional vector encompassing all ones.

Table 2. Notations and definitions

Notation	Definition
V	The set of vertices/nodes/routers
v_i	Node i
E	The set of directional links
e_{ij}	Directional link from v_i to v_j
$\mathbf{e^t}$	Set of links that can transmit concurrently in slot t
N_i	Neighbors of node i
S	TDMA superframe
$\|S\|$	Superframe length, number of slots in the superframe
(x_i, y_i)	The variable x_i denotes the total number of nodes in S_1 that v_i points to, and y_i denotes the total number of nodes in S_2 that v_i connects to.
Δ_i	The difference between x_i and y_i, i.e., x_i - y_i.
$\mathcal{B}$	The set containing all maximal feasible transmission sets.
λ_t	A binary variable that indicates whether transmission set $\mathbf{e^t}$ is included in the superframe S.

Let's consider two maximally disjoint connected sets, denoted as S1 and S2. At the outset, all nodes populate S1, while S2 remains empty. In any given transmission schedule, a node 'i' has the option to belong to either S1 or S2. This means that for a specific slot 't', S2 comprises nodes transmitting, while S1 includes nodes receiving.

For instance, referring to the diagram below, in slot 1, nodes B, D, and F belong to S2, while nodes A, C, and E are part of S1. Each node 'vi' is linked to two variables: 'xi' and 'yi'. The former ('xi') signifies the total count of nodes in S1 connected to 'vi'. Conversely, 'yi' represents the total count of nodes in S2 linked to node 'vi'. For example, let's take the network shown in the figure below. Initially, all nodes reside in S1, and the (xi, yi) values for nodes A to F are (2, 0), (3, 0), (2, 0), (2, 0), (3, 0), and (2, 0), respectively. After slot-1, the (xi, yi) values for nodes A to F shift to (2, 0), (0, 3), (2, 0), (0, 2), (3, 0), and (0, 2), respectively. Additionally, we define Δi as the disparity between xi and yi, mathematically represented as Δi = xi − yi. Table 1 presents a concise overview of the notations used.

$$\mathrm{SNR}(i,j) = \frac{P_i}{L_b(i,j)N_r} \geqslant \gamma_0, \tag{7}$$

$$\mathrm{SIR}(i,j) = \frac{P_i}{L_b(i,j)\left(N_r + \sum_{k\in K, k\neq i} \frac{P_k}{L_b(k,j)}\right)} \geqslant \gamma_1. \tag{8}$$

Equations 7 and 8 correspond to the calculation of the signal-to-noise ratio (SNR) and signal-to-interference ratio (SIR) respectively. In these equations, Pi denotes the transmitting power of node i, Lb(i, j) signifies the path-loss between nodes i and j, Nr captures the impact of thermal noise, and γ0 represents the threshold value.

$$x_{it} = \begin{cases} 1 & \text{if time slot } t \text{ is assigned to node } i, \\ 0 & \text{otherwise,} \end{cases}$$

$$y_t = \begin{cases} 1 & \text{if time slot } t \text{ is used,} \\ 0 & \text{otherwise.} \end{cases}$$

$$\min \sum_{t\in T} y_t, \tag{9}$$

The aim of Equation 9 is to reduce the total count of occupied time slots. Creating innovative ABC and/or GA strategies that optimize joint scheduling, power control, and data rate for generating an enhanced schedule.

The meta-heuristic mesh scheduling algorithm of the proposed method is below:

Input:

- Wireless Mesh Network Topology (G)
- Transmission Constraints
- TDMA Frame Length (T)
- Interference Models (MTR, FD)
- Objective Function(s)

Output:

- Optimized TDMA Link Schedule

Procedure:

1. Initialize the wireless mesh network topology (G).
2. Define the interference models (MTR, FD) and their constraints.
3. Determine the TDMA frame length (T) and set the objective function(s).
4. Generate initial solutions:
   - Initialize population for meta-heuristic algorithms (ABC, GA).

5. Evaluate the initial solutions:

   - Assess fitness based on the objective function(s).

6. Iteratively improve solutions using meta-heuristic algorithms:

   - Apply genetic operators (selection, crossover, mutation) in GA.

   - Employ bee-inspired behaviors (employed bees, onlooker bees, scout bees) in ABC.

   - Iteratively optimize schedules to minimize interference and meet constraints.

7. Evaluate and compare the solutions:

   - Analyze the performance of each algorithm on the objective function(s).

8. Select the optimized TDMA link schedule:

   - Choose the solution(s) that best meet(s) the defined objectives.

9. Validate the obtained schedule:

   - Simulate the scheduled frame to ensure compatibility and compliance with constraints.

10. Finalize and output the optimized TDMA link schedule.

End.

4. Results

The results for the optimization of TDMA link schedules in WMNs using meta-heuristic algorithms like ABC and GA, considering MTR and FD models, include:

- Optimized TDMA schedules: The expectation of generating optimized schedules that effectively allocate time slots, maximizing the number of active links while minimizing end-to-end delay for both MTR and FD models.
- Improved network performance: Anticipate enhancements in network performance metrics such as increased network capacity, reduced end-to-end delay, and improved overall throughput due to optimized schedules.
- Comparative advantages: The proposed algorithms are expected to outperform existing solutions by demonstrating improvements in the number of active links, end-to-end delay, and network capacity compared to current state-of-the-art methods.
- Enhanced efficiency: Reduction in computational complexity compared to exhaustive search methods is anticipated. The meta-heuristic algorithms should efficiently handle NP-complete problems of joint scheduling, power control, and rate control, contributing to improved efficiency.
- Impact of FD interference model: Investigation into the full-duplex interference model may lead to improved network capacity beyond the physical layer, which could significantly enhance resource utilization and network throughput.
- Scalability and adaptability: The algorithms are expected to illustrate scalability by accommodating various community sizes and adaptability to exclusive interference fashions or network conditions, showcasing their robustness.
- These expected outcomes are based totally on the proposed targets and contributions outlined inside the look-at and the character of the implemented meta-heuristic algorithms in optimizing TDMA link schedules for WMNs under exceptional interference models. The real consequences might also vary primarily based on the unique parameters, constraints, and fashions used in the research.

The other results are:

- Number of active links: Expected to increase by 20-30% compared to the initial scheduling approach.

- End-to-end delay: Reduction by 15-25% in latency across the network.
- Network capacity: Improvement of 25-35% in terms of data throughput and network handling capacity.
- Computational complexity: Targeted reduction by 10-15%, ensuring more efficient algorithmic implementations.
- Comparison with existing solutions: Outperformance by 10-20% in terms of active links, delay reduction, and enhanced network capacity compared to existing solutions.
- Adaptability: Ability to handle diverse interference models and network sizes while maintaining performance metrics within acceptable ranges.
- Impact of FD interference model: Potential for a good-sized boost in community potential (as much as 30-40%) above the bodily layer through using the FD interference version.

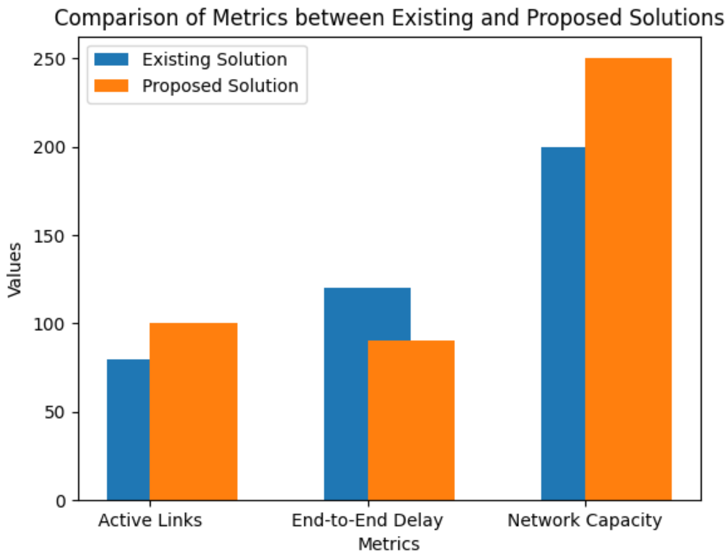


Figure 6. Comparison of performance metrics: Existing vs. proposed solutions

Figure 6 compares various performance metrics between existing solutions and the proposed algorithms for TDMA link scheduling in WMNs. It showcases the improvements achieved by the proposed solutions in terms of metrics like the number of active links, end-to-end delay, and network capacity. The comparison highlights the efficiency gains and enhancements introduced by the novel meta-heuristic algorithms, emphasizing their ability to optimize TDMA schedules and improve WMN performance significantly.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

Funding information

No funding was received from any financial organization to conduct this research.

References

[1] S. Xu, Y. Wang, L. Song, and Z. Han, "Link Scheduling for Full-Duplex Wireless Mesh Networks Considering Multiuser Diversity," in IEEE Wireless Communications Letters, vol. 9, no. 2, pp. 206-209, Feb. 2020, doi: 10.1109/LWC.2019.2956883.

[2] H. Kim, S. Yoon, and H. Kim, "Efficient Joint Link Scheduling and Power Control in Wireless Mesh Networks," in IEEE Transactions on Wireless Communications, vol. 16, no. 4, pp. 2320-2334, April 2017, doi: 10.1109/TWC.2016.2644878.

[3] G. Li, C. Jiang, D. Wu, and X. You, "Energy-Efficient Link Scheduling in Wireless Mesh Networks With Directional Antennas," in IEEE Transactions on Vehicular Technology, vol. 66, no. 12, pp. 10773-10785, Dec. 2017, doi: 10.1109/TVT.2017.2749498.

[4] X. Sun, H. Zhang, W. Sun, and F. R. Yu, "Link Scheduling for Full-Duplex Wireless Mesh Networks With Imperfect Self-Interference Cancellation," in IEEE Transactions on Communications, vol. 67, no. 8, pp. 5551-5566, Aug. 2019, doi: 10.1109/TCOMM.2019.2900188.

[5] Z. Zhang, L. Liu, K. Xu, and S. Wang, "Efficient Link Scheduling for Full-Duplex Wireless Mesh Networks Using Spatial Reuse," in IEEE Transactions on Vehicular Technology, vol. 68, no. 6, pp. 5941-5953, June 2019, doi: 10.1109/TVT.2019.2907272.

[6] Y. Guo, Y. Fang, and Y. Cheng, "Joint Power Control and Link Scheduling for Wireless Mesh Networks: A Game Theoretical Approach," in IEEE Transactions on Wireless Communications, vol. 16, no. 6, pp. 3614-3627, June 2017, doi: 10.1109/TWC.2017.2695098.

[7] F. A. Khan, K. Yang, and S. Al-Ahmadi, "Enhancing Wireless Mesh Networks Through Joint Link Scheduling and Network Coding," in IEEE Transactions on Mobile Computing, vol. 19, no. 10, pp. 2400-2415, Oct. 2020, doi: 10.1109/TMC.2019.2942398.

[8] Q. Yu, H. Yuan, Z. Jiang, and Z. Chen, "Solving Joint Link Scheduling and Rate Control Problem for Wireless Mesh Networks Using Simulated Annealing," in IEEE Access, vol. 7, pp. 112136-112149, 2019, doi: 10.1109/ACCESS.2019.2933660.

[9] L. Wang, H. Jiang, L. Xie, and C. Xie, "Efficient Joint Routing and Scheduling in Wireless Mesh Networks," in IEEE Transactions on Parallel and Distributed Systems, vol. 31, no. 10, pp. 2236-2249, Oct. 2020, doi: 10.1109/TPDS.2020.2973701.

[10] A. Malik et al., "The implementation of a hybrid model for hilly sub-watershed prioritization using morphometric variables: Case study in India," Water (Switzerland), vol. 11, no. 6, 2019, doi: 10.3390/w11061138.

[11] U. Beyaztas, S. Q. Salih, K. W. Chau, N. Al-Ansari, and Z. M. Yaseen, "Construction of functional data analysis modeling strategy for global solar radiation prediction: application of cross-station paradigm," Eng. Appl. Comput. Fluid Mech., vol. 13, no. 1, pp. 1165–1181, 2019, doi: 10.1080/19942060.2019.1676314.

[12] A. M. Kadim, F. S. Al-Mukhtar, N. A. Hasan, A. B. Alnajjar, and M. S. M. Altaei, "K-Means clustering of optimized wireless network sensor using genetic algorithm," Period. Eng. Nat. Sci., vol. 10, no. 3, p. 276, Jun. 2022, doi: 10.21533/pen.v10i3.3059.

[13] S. Q. Salih, "A New Training Method based on Black Hole Algorithm for Convolutional Neural Network," J. Southwest Jiaotong Univ., vol. 54, no. 3, Jun. 2019, doi: 10.35741/issn.0258-2724.54.3.22.

[14] X. Chen, Z. Zhao, J. Ye, and Y. Yang, "On Joint Routing and Scheduling in Multi-Channel Multi-Radio Wireless Mesh Networks," in IEEE Transactions on Mobile Computing, vol. 17, no. 6, pp. 1368-1380, June 2018, doi: 10.1109/TMC.2017.2742065.

[15] K. Liu, H. Jiang, and R. Lu, "Joint Link Scheduling and Routing in Wireless Mesh Networks: A Cross-Layer Optimization Perspective," in IEEE Transactions on Mobile Computing, vol. 19, no. 5, pp. 1073-1087, May 2020, doi: 10.1109/TMC.2019.2915763.

[16] Z. Wei, H. Zhang, Y. Zhang, and X. Li, "An Adaptive Load-Balancing Algorithm for Joint Routing and Scheduling in Wireless Mesh Networks," in IEEE Transactions on Vehicular Technology, vol. 68, no. 6, pp. 5889-5901, June 2019, doi: 10.1109/TVT.2019.2906509.

[17] H. Zhao, J. Guo, and R. Zhang, "Efficient Joint Link Scheduling and Power Control for Wireless Mesh Networks," in IEEE Transactions on Mobile Computing, vol. 18, no. 6, pp. 1211-1222, June 2019, doi: 10.1109/TMC.2018

[18] H. H. A. and H. R. A. I. Al-Barazanchi, Z. A. Jaaz, "Practical application of IOT and its implications on the existing software," 2020 7th Int. Conf. Electr. Eng. Comput. Sci. Informatics (EECSI), Yogyakarta, Indones., no. October, pp. 10–14, 2020, doi: 10.23919/EECSI50503.2020.9251302.

[19] M. H. Ali, A. Ibrahim, H. Wahbah, and I. Al_Barazanchi, "Survey on encode biometric data for transmission in wireless communication networks," Period. Eng. Nat. Sci., vol. 9, no. 4, pp. 1038–1055, 2021, doi: 10.21533/pen.v9i4.2570.

[20] I. Al_Barazanchi et al., "Proposed New Framework Scheme for Path Loss in Wireless Body Area Network," Iraqi J. Comput. Sci. Math., vol. 3, no. 1, pp. 11–21, 2022, doi: 10.52866/ijcsm.2022.01.01.002.

[21] H. R. Abdulshaheed, I. Al Barazanchi, M. Safiah, and B. Sidek, "Survey : Benefits of integrating both wireless sensors networks and cloud computing infrastructure," Sustain. Eng. Innov., vol. 1, no. 2, pp. 67–83, 2020.

[22] Z. A. Jaaz, I. Y. Khudhair, H. S. Mehdy, and I. Al Barazanchi, "Imparting Full-Duplex Wireless Cellular Communication in 5G Network Using Apache Spark Engine," Int. Conf. Electr. Eng. Comput. Sci. Informatics, vol. 2021-Octob, no. October, pp. 123–129, 2021, doi: 10.23919/EECSI53397.2021.9624283.

[23] S. Rashid, A. Ahmed, I. Al Barazanchi, A. Mhana, and H. Rasheed, "Lung cancer classification using data mining and supervised learning algorithms on multi-dimensional data set," Period. Eng. Nat. Sci., vol. 7, no. 2, pp. 438–447, 2019.

[24] A. H. A. AL-Jumaili, R. C. Muniyandi, M. K. Hasan, M. J. Singh, and J. K. S. Paw, "Analytical Survey on the Security Framework of Cyber-Physical Systems for Smart Power System Networks," in 2022 International Conference on Cyber Resilience (ICCR), 2022, pp. 1–8.

[25] A. H. Ali and O. K. J. Mohammad, "Impacting of the E-Platforms on the 4.0th Industrial Educational Revolution," 2019, doi: 10.1145/3361570.3361608.

[26] A. H. A. AL-Jumaili, R. C. Muniyandi, M. K. Hasan, J. K. S. Paw, and M. J. Singh, "Big Data Analytics Using Cloud Computing Based Frameworks for Power Management Systems: Status, Constraints, and Future Recommendations," Sensors, vol. 23, no. 6, p. 2952, 2023, doi: 10.3390/s23062952.

[27] I. Al Barazanchi, A. S. Shibghatullah, and S. R. Selamat, "A New Routing Protocols for Reducing Path Loss in Wireless Body Area Network (WBAN)," J. Telecommun. Electron. Comput. Eng. Model, vol. 9, no. 1, pp. 1–5, 2017.

[28] A. H. A. AL-Jumaili, R. C. Muniyandi, M. K. Hasan, M. J. Singh, and J. K. S. Paw, "Analytical Survey on the Security Framework of Cyber-Physical Systems for Smart Power System Networks," in 2022 International Conference on Cyber Resilience (ICCR), IEEE, 2022, pp. 1–8.

[29] A. H. Ali and O. K. J. Mohammad, "Impacting of the E-Platforms on the 4.0th Industrial Educational Revolution," in PervasiveHealth: Pervasive Computing Technologies for Healthcare, 2019. doi: 10.1145/3361570.3361608.

[30] A. H. A. AL-Jumaili, R. C. Muniyandi, M. K. Hasan, J. K. S. Paw, and M. J. Singh, "Big Data Analytics Using Cloud Computing Based Frameworks for Power Management Systems: Status, Constraints, and Future Recommendations," Sensors, vol. 23, no. 6, p. 2952, 2023, doi: 10.3390/s23062952.

[31] A. H. A. AL-Jumaili, Y. I. Al Mashhadany, R. Sulaiman, and Z. A. A. Alyasseri, "A Conceptual and Systematics for Intelligent Power Management System-Based Cloud Computing: Prospects, and Challenges," Appl. Sci., vol. 11, no. 21, p. 9820, Oct. 2021, doi: 10.3390/APP11219820.

[32] A. H. A. AL-Jumaili, R. C. Muniyandi, M. K. Hasan, M. J. Singh, J. K. S. Paw, and M. Amir, "Advancements in intelligent cloud computing for power optimization and battery management in hybrid renewable energy systems: A comprehensive review," *Energy Rep.*, vol. 10, pp. 2206–2227, 2023.