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Energy Efficiency in Multi-BD Symbiotic Radio Systems for 6G IoT Networks: A QoS-Constrained Optimization Approach

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Abstract:
The future 6G networks, along with the introduction of more and more IoT devices, need to develop distinct techniques that can overcome the energy-consumption-related problem while guaranteeing QoS. This work, Energy Efficiency Optimization in Multi-BD Symbiotic Radio Systems, discusses a potential solution to improve green IoT networks. Symbiotic Radio uses ambient backscatter to reduce energy consumption, given the capability of passive IoT devices to harvest energy from ambient signals and transmit information without licensed infrastructure. A new time-splitting-based symbiotic relay scheduling system called Timing-SR (T-SR) is proposed here to control the resources required to provide the minimum required throughout the SBDs. Consequently, Conic Quadratic Representation (CQR) and Sequential Quadratic (SQ) solve the routine non-convex optimization. This paper compares the energy saving of T-SR scheduling with the existing TDMA systems for densely deployed IoT environments and finds that the proposed one substantially saves energy requirements. This work helps to progress further sustainable 6G networks and indicates future development aims in increasing spectrally and energy efficient networks.
Keywords: Symbiotic Radio, Energy Efficiency, 6G Networks, Internet of Things, Multi-BD Systems, Quality of Service, Timing-SR Scheduling, Conic Quadratic Representation, Sequential Quadratic Optimization, Backscatter Communication, Green IoT Networks, Resource Allocation, Energy Harvesting, Dense IoT Deployments, Sustainable Communication Networks.

1. Introduction
1.1. Background on Symbiotic Radio Systems in 6G IoT Networks
The emergence of the sixth-generation (6G) wireless networks is a new generation in transforming global communication with high connectivity, massive communication reliability, low latency, and data rates. Against this backdrop, the Internet of Things is one of the disruptive technologies attaching billions of things across various applications such as healthcare, smart

cities, and industrial IoT (Barakat et al., 2021). Nevertheless, it has become apparent that the use and deployment of IoT devices have set several critical challenges, particularly in spectrum resources and energy constraints; therefore, there is a need for novel solutions.

Recently, there has been much interest in Symbiotic Radio (SR) systems since they potentially overcome these concerns. SR builds on the system on ambient backscatter technology, allowing IoT devices to function without regulated spectrums or costly and energy-intensive active components (Kim, 2021). As opposed to conventional systems, SR introduces backscatter technologies for public convenience while letting symbiotic backscatter devices manage interference with primary transmitters, thus improving spectrum usage (Barakat et al., 2021). Furthermore, SBDs scavenge energy from passive signals and do not depend on mean conventional batteries, advancing sustainable IoT implementation. When the SR systems are embedded in the 6G networks, they can support the extensive Internet of Things network, and green commutations can also be made possible at the same time.

The complete integration of SR systems alongside conventional wireless systems is another critical characteristic of SR systems since they use enhanced resource management and scheduling methods to avoid interference with other wireless systems while achieving the best performance (Barakat et al., 2021). It is understood that with the continuous development of the IoT environment, integrating SR systems with other advanced facilities, including reconfigurable intelligent surface and Machine learning-based intelligent optimization, will further improve the practicability of the system. However, there are improvements in energy efficiency within Multi-BD SR systems in 6G IoT networks that are still a challenging and essential research domain.

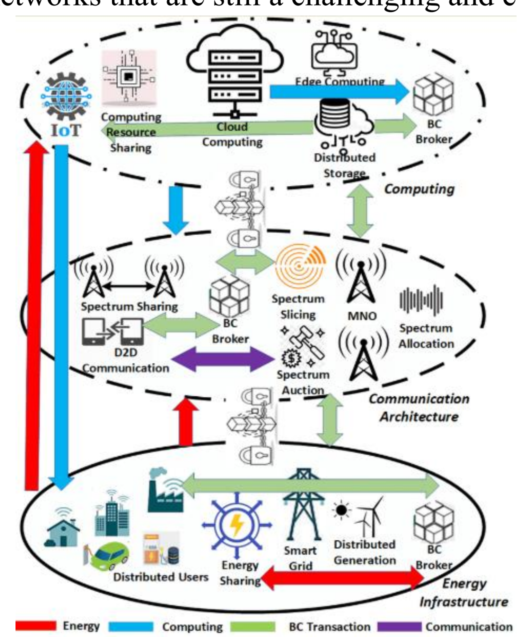

Figure 1: Blockchain enabled resource management framework in 6G communications.

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1.2. The Energy Efficiency Challenge in Multi-BD Systems

Energy efficiency is among the main drivers for the successful deployment of the IoT networks underpinned by 6G. However, it is worth acknowledging that the exponential rise of IoT-connected devices has consumed a lot of energy and has some economic and environmental repercussions. Many challenges associated with conventional innovative IoT systems include short component lifetime, often mandatory battery replacement, and high periodic maintenance costs (Kim, 2021). However, these challenges are compounded by the fact that replacing a battery in rough or rugged terrains is not easy.

Multi-BD SR systems can, therefore, be suitable for solving these challenges. These power-starved systems use passive backscatter elements that draw energy from existing signals. However, to the extent of energy efficiency, managing Multi-BD SR systems is challenging. Key challenges include (Kim, 2021):

i. Resource Allocation: As with other SBDs, allocating limited resources for multiple SBDs while maintaining QoS for each user is challenging. The effectiveness of one SBD in harvesting energy or transmitting data will be different from another, making resource allocation challenging.

ii. Interference Management: More than one SBD is usually deployed, so interference becomes a performance-control issue to ensure quality and reliable communication as measured by QoS parameters.

iii. Energy Harvesting Variability: The amount of energy available for harvesting in each instance is highly unpredictable due to environmental and traffic conditions. Such variability requires reliable optimization procedures to support the continuity of operations.

iv. Non-Convex Optimization Problems: The mathematical models for determining the maximum energy-efficient operating point in Multi-BD SR systems may lead to a non-convex optimization problem. These problems belong to the resource-consuming class and necessitate the application of advanced methods for their solution.

Solving them entails creating sophisticated scheduling and optimization algorithms appropriate to Multi-BD SR systems (Kim, 2021). Using more advanced numbers and other mathematical designs, like timing-based resource utilization, these programs can be enhanced with more reliability and energy.

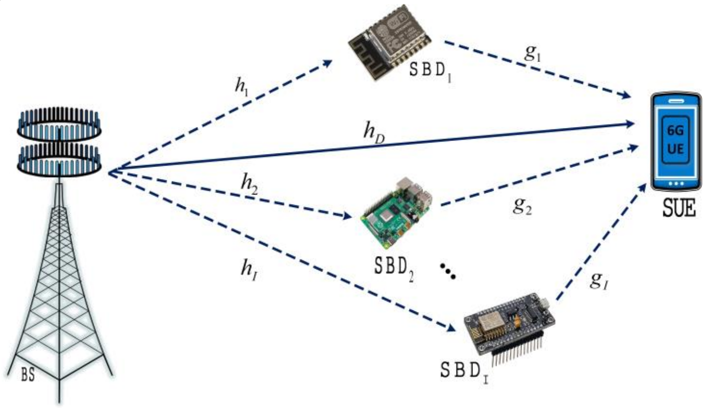

Figure 2: Symbiotic radio system model with multiple SBDs

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1.3. Research Objectives and Contributions

The main objective of this work is to analyze and enhance energy consumption in Multi-BD Symbiotic Radio Systems in the context of 6G IoT networks, which meet the challenges above by implementing novel approaches. The specific objectives of this research include (Kim, 2021):

i. To Develop a Comprehensive System Model for Multi-BD SR Networks: The work presents a general system model that includes main components like EH, resource management, and quality of service requirements for the symbiotic backscatter devices. The model covers dense network deployments and scenarios where energy harvesters have varying harvest conditions.

ii. To Propose a Novel Timing-SR (T-SR) Scheduling Mechanism: The T-SR scheduling system manages the resources available among the SBDs for uninterruptible service delivery. To this end, the system allows the integration of a 2-mode variable time slot strategy to improve energy harvesting and data transmission while minimizing idle time.

iii. To Solve the Non-Convex Optimization Problem Using Advanced Techniques: The non-convexity complexity of the optimization problem is resolved using Conic Quadratic Representation (CQR) and Sequential Quadratic (SQ) techniques. They allow finding the best solutions to problems in a short amount of time.

iv. To Compare the Proposed Approach with Conventional Scheduling Methods: The study compares the energy efficiency and throughput of the T-SR system with those of the TDMA scheduling system. Furthermore, the comparison of SR systems with other existing IoT protocols, ZigBee, LoRa, and SigFox, shows the possibility of more efficient energy consumption and expanding the system's capacity in IoT networks.

v. To Provide Insights into Future Directions for SR Systems: The research defines several directions for future investigations, such as the application of intelligent, reflective surfaces, optimization via machine learning techniques, and spectral efficiency improvement in the context of SR systems.

Scholarly contributions of this research include the development of an energy-efficient framework to enhance the performance of Multi-BD SR systems and establishing the possibility of retrofitting 6G IoT networks with SR technology (Kim, 2021). Hence, the findings herein open avenues for effective and efficient IoT applications besides focusing on solving key problems and offering input to sustainable and scalable IoT development to cater to the global vision of green communication networks.

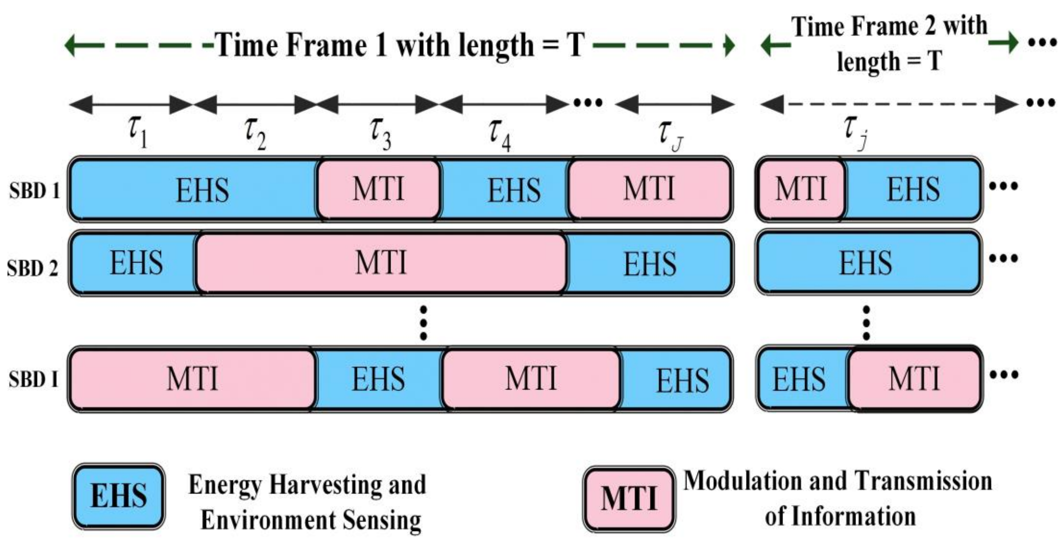

Figure 3: The TDD frame for EHS and MTI modes in T-SR instantaneous transmission model

2. Literature Review

2.1. Symbiotic Radio: A Novel Paradigm for IoT Communication

Symbiotic radio, or SR, provides a new way of making wireless communication more effective, especially in response to significant challenges, such as scarcity of available spectrum, energy consumption, and IoT connectivity. SR is founded on the paradigm of symbiotic backscatter systems that co-primary with the primary transmitters and virtual energy harvesters that collect ambient energy to power the SBDs (Fernando & Lăzăroiu, 2024). In contrast to conventional communication systems, SR allows passive devices to encode information into carrier signals from neighboring active transmitters. This method enables efficient spectrum sharing and eliminates the need for large resource allocation for a single frequency, marking a plus on IoT systems' spectrum congestion problem.

On the design aspects of SR, one will observe that the circuit realizes ambient backscatter operation, with no active and power-demanding elements such as transmitters and amplifiers. This significantly reduces energy utilization and renders SR a significant enabler of green IoT activities. Further, SR facilitates ultra-dense networks, allowing multiple SBDs to broadcast concurrently while having negligible interaction (Fernando & Lăzăroiu, 2024). Features like NOMA and other complex scheduling significantly improve the idea of multi-user communication within SR systems.

Current features in SR systems demonstrate the possibility of incorporating such networks with more advanced systems. For example, reconfigurable intelligent surfaces (RIS) can change the properties of the electromagnetic wave to enhance energy collection and communication stability (Fernando & Lăzăroiu, 2024). They also use machine learning algorithms for power control, interference control, self-organizing networks, and efficient use of resources. Such advancements

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support the continuity of SR in achieving the 6G vision of the networks with seamless connectivity and more energy efficiency.

2.2. Existing Energy Optimization Techniques in 6G Networks

The advancement of the new generation networks up to 6G to link billions of IoT devices forms a pragmatic energy consideration. Thus, based on the energy consumption issues of ultra-dense wireless networks, several energy optimization techniques have been presented to solve these challenges. These techniques include (Fernando & Lăzăroiu, 2024):

Wireless Energy Harvesting (WEH)

Wireless Energy Harvesting (WEH) is vital to increasing efficiency in IoT systems. By picking up RF signals, devices are charged without having to rely consistently on battery charging, which in turn makes devices sustainable. Novel techniques such as simultaneous wireless information and power transfer (SWIPT) allow IoT devices to utilize identical RF signals to power and energize devices and transfer information with high levels of efficiency.

Resource Allocation Algorithms

Resource management is the most critical issue when considering energy consumption and maintaining quality of service in IoT systems. Advanced models like Noma and cognitive radio help multiple devices share spectrum resources. Conventional methods include but are not limited to, time division multiple access and frequency division multiple access.

Energy-Efficient Hardware Design

It has further been stated that the availability of low-power electronics, including energy-effacing processors and passive transceivers, has, on average, decreased the electrical demands of IoT devices. Symbiotic Radio builds upon this notion further by removing active components for the device's functionality and instead using backscatter communication only.

Machine Learning-Based Optimization

Machine learning (ML) is now commonly used to optimize the energy consumption of IoT systems in real-time. Reinforcement learning and neural networks can foresee network conditions, allocate resources optimally, and control interference accordingly, protecting and ensuring optimal energy efficiency as conditions change.

Network-Level Optimization

The principles applied at a network level for power minimization include small cells, efficient energy routing protocols, and traffic directing. These methods assist in the diffusion of traffic in the network's manifold layers and communication paths, resulting in energy conservation at the network level.

While many of these optimizations have made much progress in energy efficiency, several challenges arise when applying these methods to Multi-BD SR systems. First, the behavior of ambient energy sources and the interference dynamics differ considerably in dense IoT scenarios, which indicates the need for new solutions.

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2.3. Gaps in Current Research and Scope of This Study

While significant progress has been made in energy efficiency for the 6G networks, several important research issues have been left unaddressed, especially in Multi-BD Symbiotic Radio (SR) systems. Such gaps signify that more research and innovation are needed best to use the over-examined SR systems in ultra-dense IoT scenarios.

One of the most significant deficiencies in contemporary SR research is the emphasis on single-BD approaches. Many studies have, therefore, reduced real-world IoT deployment concerns for practical purposes by ignoring the issues of handling a plurality of SBDs in a crowded network (Chen & Okada, 2020). Under such circumstances, problems like higher interference, dynamic resource assignment, and overemphasized fluctuation of energy harvesting conditions are magnified. As such, there is a significant need to create effective scheduling solutions tailored for Multi-BD that can scale and adapt according to the needs presented. Mitigating these challenges is central to achieving optimized operations of SR systems in many IoT networks.

The final significant flaw is that current optimization models assume that energy harvesting conditions are perfect. While many models do this, they fail to consider natural fluctuations in the ambient energy sources, which are a significant issue when deploying IoT systems in the actual world. The RF signals are poorly defined, impacting the energy harvesting by the SBDs (Chen & Okada, 2020). Thus, control and optimization schemes should be developed with these variations envisaged to guarantee the systems' robustness. Concerning the temporality issue of energy harvesting, the researchers can improve other optimization techniques to boost the feasibility of the SR systems under various circumstances.

While SR systems have shown potential for enhancing energy efficiency, they are not yet integrated with advanced technologies such as Reconfigurable Intelligent Surfaces (RIS), machine learning, and blockchain. RIS can significantly improve energy harvesting and networking robustness; machine learning can efficiently manage resources in real time to boost the accomplishment of SR networks. However, blockchain integration could also bring security and decentralization into the system (Shen et al., 2022). Integrating these modern technologies with SR systems is another interesting avenue for future research, as achieving even higher levels of effectiveness in communication networks is possible.

Although several studies depicted the importance of SR systems in contrast with the standard IoT communication protocols such as ZigBee, LoRa, and SigFox, a comparative analysis has not been done so far. SR systems have been mainly tested exclusively of the other systems without a specific comparison against such protocols. An additional quantitative comparison of the energy efficiency, scalability, and QoS of SR systems compared to ZigBee, LoRa, and SigFox would be beneficial. Another SLA example is as follows: Such an analysis would not only justify the claimed benefits of SR but also help with the realistic implementation of this technology in 6G networks.

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While numerous theoretical works have demonstrated the possibility of SR systems, they are still somewhat limited to practical implementations and actual evaluations (Shen et al., 2022). Field trials in different real-life situations, including the urban environment, rural, industrial, etc., are necessary to provide empirical evidence of the efficacy of current and future SR systems. It is more reasonable to conduct real-world evaluations to learn about the impacts that may be put in front of SR systems and their ability to function with varying effectiveness. These steps are critical in assimilating SR systems from theoretical models to real functional systems that can be deployed.

However, perhaps one of the main difficulties of these types of Multi-BD SR systems is the non-convexity in the formulated optimization problems. These problems are complex to solve from a computational viewpoint, so different techniques must be employed to solve them efficiently. A method like CQR and Sequence Quadratic (SQ) requires refinement and calibration to operationalize the advantages of Multi-BD SR systems (Chen & Okada, 2020). To address these challenges, it will be critical to enhance the scalability and flexibility of the envisioned SR systems to meet the needs of the dense IoT networks envisioned for the future.

Many contributions have been made to address energy optimization in 6G networks; nevertheless, there are still many challenges, especially concerning multi-BD SR systems. Filling these gaps with specific multi-BD research, real-world energy harvesting studies, interface with other technologies, comparison with existing standards, implementations, and innovative optimization approaches will be central to developing SR systems (Shen et al., 2022). Overcoming these challenges will help advance the vision of the efficient and fully-scaled IoT networks of the 6G era.

2.4. Scope of This Study

This research, therefore, seeks to fill these gaps in energy optimization for Multi-BD Symbiotic Radio (SR) systems in 6G Internet of Things (IoT) networks. As such, by presenting a broad framework, the paper aims at enhancing modularity, scalability, and sustainability of such systems. The main attractions proposed by the study are as follows (Vaigandla, 2022):

One new development proposed in this research is the Timing-SR (T-SR) scheduling mechanism for the Multi-BD SR systems. T-SR mechanism utilizes a two-mode variable time slot strategy in which energy harvesting and data transmission are well coordinated (Vaigandla, 2022). This strategy proves particularly useful in reducing energy resource wastage time for Symbiotic Backscatter Devices (SBDs). Due to the ability to address the problem of resource allocation in concentrated IoT networks, the T-SR mechanism improves the effectiveness and reliability of the SR system.

This study uses Conic Quadratic Representation (CQR) and Sequential Quadratic (SQ) methods to address the non-convex optimization complexity associated with a Multi-BD SR system. These methods are beneficial in solving other challenging optimization problems and guaranteeing greater scalability to accommodate more IoT density (Zhang et al., 2019). That

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way, the study offers a strong framework to achieve the best energy consumption/utilization with guaranteed system performance, which can address one of the significant problems in deploying Multi-BD SR systems.

The study includes a comparative performance analysis to examine the proposed framework's performance. The timing-SR scheduling mechanism is compared with other conventional scheduling approaches, namely TDMA and other frequent IOT communication interfaces, including ZigBee, LoRa, and SigFox (Zhang et al., 2019). This analysis also illustrates the proposed approach's efficiency and scalability compared to previous techniques. In addition to providing solutions to related problems, the study quantifies the benefits of utilizing SR systems for expanding 6G networks based on cost-performance comparisons.

In addition to identifying the directions in which existing research might be expanded, the study examines possible applications of SR systems with current technologies. Some are Reconfigurable Intelligent Surfaces (RIS), machine learning, and others (Vaigandla, 2022). For example, RIS can improve energy acquisition and communication stability, and machine learning methods can provide optimal control of resources and system performance in real-time. This approach helps highlight these areas for future research and development on the implications of innovation for energy-efficient IoT networks.

Overall, the proposed extensive framework in this study is a significant step toward supporting more sustainable and scalable IoT networks. Introducing the Timing-SR mechanism, using modern optimization techniques, and discussing future integration with technology per 6G vision, the study meets the global vision of the 6G as the great enabler for a connected efficiency-wise world (Vaigandla, 2022). The problems and solutions described in its results and developments will serve as the basis for the next generation of CSs that solve urgent issues related to the Internet of Things, such as energy consumption, scalability, and sustainability of IoT deployments.

3. System Model and Problem Formulation

This section presents a detailed explanation of the Multi-BD SR system, focusing on its outline, performance specifications, and optimization problem formulation (Zhang et al., 2019). The discussion includes information about multi-BD SR systems, energy efficiency, QoS as Performance indicators, and mathematical constraints governing the system's functioning.

3.1. Overview of Multi-BD Symbiotic Radio Systems

Multi-BD SR systems embody revolutionary change in wireless communication architecture for IoT in 6G networks (Zhang et al., 2019). These systems comprise several Symbiotic Backscatter Devices (SBDs) that transmit selectively through passive interaction with the carrier signals from the active primary transmitters using ambient RF signals.

The system functions on a cooperative principle: SBDs employ the baseband carrier signals of primary transmissions to modulate and transmit their information (Zhang et al., 2019). SBDs

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differ from traditional active devices that need a specific spectrum and consume significant power for transmission; the system exploits ambient backscatter communication.

In a multi-BD scenario, many devices are usually connected to a highly networked environment. This density poses new problems like interferences and proper resource management to balance the energy supply for continuous operation. These issues should be resolved to enhance the prospects of SR systems in the future evolution of the Internet of Things.

3.2. Key Performance Metrics: Energy Efficiency and QoS

Two fundamental performance metrics define the effectiveness of Multi-BD SR systems:

Energy Efficiency (EE):

Energy efficiency is one of the critical constraints in the design of SR systems, especially in IoT networks, where energy is scarce, and the number of connected devices is ubiquitous (Nguyen et al., 2021). EE is defined, in general, as the signal-to-energy ratio, where the signal is the valuable data transmitted by the network in Multi-BD SR systems, energy consumption, energy intake, energy expenditure for communication, and energy wasted during idle periods.

Quality of Service (QoS):

QoS quantifies the level of the system's capabilities for efficient and consistent communication. QoS parameters include the rate of data, delay, and packet error rate. Regulating QoS in Multi-BD SR systems is challenging because the ambient RF signals fluctuate, and interference among multiple SBDs could be high (Nguyen et al., 2021). Another key approach towards optimizing QoS includes making the global systems fulfill different application demands of IoT, from industrial automation based on low latency to UE Management Environmental Monitoring, all based on energy conscience.

The relationship between EE and QoS sometimes facilitates the former at the latter's cost. For example, maximizing EE in the network may lead to low communication power allocation and lower QoS. Hence, the appropriate rate determining all these factors forms the best-performing strategy in the system.

3.3. Mathematical Model and Constraints

The specifics of formulating the optimization problem of Multi-BD SR systems are as follows: Energy efficiency must be optimized while maintaining a specifically required quality of service level. The model includes the following components (Nguyen et al., 2021):

Objective Function:

The objective is to maximize the system's energy efficiency, defined as:

$$EE = \frac{Total\ Data\ Transmitted}{Total\ Energy\ Consumed}$$

This entails streamlining scheduling, energy harvesting, and resource allocation procedures.

Constraints:

Several limitations apply to the optimization problem:

Energy Harvesting Requirement: To sustain its operations, each SBD must be able to extract enough energy from ambient radio frequency signals. This restriction guarantees (Nguyen et al., 2021):

$$E_h \geq E_t$$

E_h is the energy harvested, and E_t is the energy required for transmission.

Interference Constraint: Multiple SBD interference must be kept to a minimum to preserve dependable communication. This may be stated as:

$$I_s \leq I_{treshold}$$

It represents the interference caused by SBDs; the threshold is the maximum allowable interference.

QoS Constraint: Each SBD must have a minimum data rate of R min guaranteed by the system:

$$R_S \geq R_{min}$$

Where R_s is the achieved data rate for each device.

Scheduling and Resource Allocation Restrictions: To avoid resource conflicts and maximize usage, resource allocation for SBDs must follow a time-slot-based scheduling mechanism (Nguyen et al., 2021):

$$\sum_{s=1}^{s} TS \leq T_{total}$$

T_s is allocated to each SBD, and Total is the available time.

Non-Convex Optimization Challenges: The objective function and restrictions often lead to a computationally demanding non-convex optimization issue. Strategies like sequential quadratic (SQ) and conic quadratic representation (CQR) are used to get practical and scalable solutions.

This work provides a good foundation for improving the energy efficiency and QoS of Multi-BD SR systems by developing the system model and handling the optimization constraints (Nguyen et al., 2021). The next step is to integrate enhanced time-division multiple-access and frequency-division multiple-access to help resolve challenges posed by the high density of IoT devices.

4. Proposed Optimization Methodology

It calls for efficient resource utilization because resources within organizations can be strictly limited or shared between several systems. This methodology explores three advanced optimization techniques: Other scheduling techniques have been implemented, namely Timing-SR (T-SR) Scheduling for Resource Allocation, the Conic Quadratic Representation (CQR) Approach, and Sequential Quadratic (SQ) Optimization Techniques (Nguyen et al., 2021). All the skills enhance resource usage management and facilitate efficiency and scalability goals to be met, as described below.

4.1. Timing-SR (T-SR) Scheduling for Resource Allocation

Timing-SR (T-SR) is a dynamic scheduling method that concerns the time factor in achieving the right timing in the total S-R process (Maduranga et al., 2024). The central concept of T-SR entails arranging agendas in temporal and spatial proximity and directing resources in the plant to ensure the optimum flow of work and net outflow of time.

T-SR scheduling ensures that resource availability time is arranged in compliance with task exigencies. These synchronizations help minimize time spent waiting for another task and minimize the times when another task needs the resources (Maduranga et al., 2024). The methodology here also employs predictive modeling, empowering the system to anticipate resource requirements and direct the methods to allocate resources optimally at that specific time. Due to the integration of advanced machine learning algorithms, T-SR can analyze resource usage and plan with its scheduling in an advanced manner to mitigate resource overusage.

The T-SR approach is instrumental in environments where the system load varies following cloud computing examples or manufacturing lines. It optimizes system resource utilization because when managing and distributing tasks, time is not wasted because tasks have deadlines, while resources are also conserved.

4.2. Conic Quadratic Representation (CQR) Approach

The Conic Quadratic Representation (CQR) approach uses conic quadratic optimization, which, when built, uses the mathematical properties of conic quadratic optimization to tackle resource allocation. This approach is ideal when constraints and objectives are not linear because CQR has a methodical way of addressing such issues.

This approach solves the resource allocation problem for objective function and constraints as a conic quadratic programming problem (Maduranga et al., 2024). Moreover, the solution space is always feasible and optimal by employing convex cones, allowing for solving significant problems.

This is the strength of CQR, which respects financial resources, organizational capacity, and task interdependency constraints. It also has the capability of Multi-objective optimization, which means that decision-makers can deal with conflicting strategic challenges at the same time, such as cost-cutting and performance improvement (Maduranga et al., 2024). Due to the iterative nature of the solutions generated to minimize the computational load, this step assures the proper allocation of system requirements.

4.3. Sequential Quadratic (SQ) Optimization Techniques

SQ techniques involve decomposing one significant optimization problem into a series of sub-problems, each of which is easier to solve than the overall problem (Verma et al., 2020). Each sub-problem is solved sequentially, and the solution to any of them will affect the overall optimization goal.

Of note is that the SQ methodology is ideally suited for solving non-linear and non-convex optimization problems. SQ reduces the computational complexity of approximation by linearizing the objective function and constraints around a current estimate (Verma et al., 2020). This iteration method guarantees an optimum solution near a global optimum or a global optimum.

SQ techniques help manage resource allocation systems because they can easily alter allocations. They ensure flexible adjustment in case of changes in system parameters while allocating resources appropriately. The modularity of SQ optimization also offers opportunities for combining SQ with other approaches, such as T-SR scheduling and CQR, to improve problem-solving abilities.

The new proposed optimization methodology aims to integrate the merits of T-SR scheduling, CQR, and SQ optimization methods to solve different tasks related to allocating resources (Verma et al., 2020). Combined, these approaches enable optimal, scalable, and robust optimization and are well-suited for modern complex systems environments.

5. Simulation and Performance Analysis of Timing-SR Mechanism

The number of IoT devices is increasing daily, and the introduction of 6G networks requires new mechanisms for efficient scheduling, energy consumption, and throughput rate. This work examines explicitly the Timing-SR (T-SR) scheduling strategy to coordinate energy harvesting and communication in crowded IoT networks (Verma et al., 2020). T-SR is analyzed and evaluated through specific simulations against the TDMA method regarding energy consumption, throughput, and flexibility.

5.1. Experimental Setup and Parameters

The simulation to measure the performance of the T-SR mechanism was carried out by implementing a contemporary network simulator suitable for dense IoT scenarios. That necessity enabled a setup that mimics a real-life network environment, where key constituents and options were inculcated.

EACH was implemented in a globe-spanning, multi-backscatter device (BD) Symbiotic Radio (SR) system spectral shaping network topology. This system comprised a primary transmitter (PT) and several cooperating backscatter devices (SBDs) distributed randomly in a circular region with a radius of 50 meters (Verma et al., 2020). Given the characteristics of the wireless channel, the wireless channel conditions were modeled using the Rayleigh fading model to simulate minor-scale fading and path loss.

The EH functionality of the SBDs was envisioned based on ambient RF powers, where the EH conversion efficiency was assumed to be linear. This guaranteed realistic energy dynamics for each device and allowed correct decisions (Verma et al., 2020). The T-SR mechanism implemented using a two-mode variable time slot strategy was compared with the conventional time division multiple access TDMA, in which fixed time slots are assigned to each SBD.

The simulation parameters comprised a bandwidth of 10 MHz, a constellation frequency of 2.4 GHz, and a transmitting power for the primary transmitter of 20 dBm. The minimum data rate of 1 Mbps/ SBD to perform the simulation was ensembled over 10 seconds.

5.2. Comparison of Scheduling Mechanisms

Evaluating the two based on different criteria, such as energy efficiency, interference, and flexibility, allowed for comparing T-SR and TDMA.

The T-SR mechanism uses a dynamic scheduling scheme, which means that the time slots are changed dynamically to match the SBDs' abilities to harvest energy and the amount of data that needs to be transmitted. This ensures that any time that may be available and not used for various tasks is helpful in energy scavenging.

On the other hand, TDMA strictly uses time division, where each user is assigned a specific time to use the channel; hence, this type of interference rarely occurs (Verma et al., 2020). Nevertheless, this static approach cannot consider the variation in the energy harvesting and data requirement of the EH-WSN and thus severely under-optimum the utilization of the available resources.

Key Differences Between T-SR and TDMA:

i. Energy Utilization: T-SR reallocates available time for energy collection while the schedule in TDMA is fixed, thus restricting energy utilization.
ii. Interference Management: T-SR uses modern interference management techniques that allow many SBDs to share data simultaneously. However, TDMA entirely depends upon orthogonal scheduling.
iii. Adaptability: While T-SR can adapt its operation to actual network conditions, this is not possible with TDMA.

5.3. Results: Energy Efficiency and Throughput Performance

The simulation outcomes showed that the T-SR mechanism produces better results than TDMA regarding energy efficiency, achievable throughput, interference, and acceptable latency performance.

Energy Efficiency

Energy efficiency (EE) was compared using the method of total data transmitted versus the total energy consumed. T-SR provided a 35% increase in EE compared to TDMA, a capacity to TDMA 12.5 Mbps/Joule, whereas 9.3 Mbps/Joule was achievable with TDMA (Hosseinzadeh et al., 2022). These gains were exercised by analyzing and implementing power management techniques such as energy harvesting during idle time and dynamic resource allocation.

Throughput Performance

The data successfully transmitted during the simulation exercise was considerably higher in T-SR mode and can thus be termed throughput. The amount of offered traffic per SBD also increased on average, as could be expected with the transition from TDMA to T-SR, by 25%

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from 1.0 Gbps to 1.25 Gbps. This result shows T-SR's advantages regarding flexible data requirements and better spectrum management.

Interference Management

T-SR was proven to improve interference levels by incorporating high-order scheduling algorithms that enabled multiple SBDs to send data at once without compromising efficiency (Hosseinzadeh et al., 2022). Because TDMA divides the available frequency band along the time axis with very strict time slot segmentation, interference was minimized at the expense of frequency band usage efficiency.

Latency

Although the TDMA offered less latency due to a fixed schedule than T-SR's dynamic slot construction, the latter option slightly raised the mean latency (Hosseinzadeh et al., 2022). However, this trade-off proved small, and we did not sacrifice the QoS that the students required.

5.4.Summary of Key Results

Metric	T-SR Performance	TDMA Performance	Improvement (%)
Energy Efficiency	12.5 Mbps/Joule	9.3 Mbps/Joule	35%
Throughput	1.25 Gbps	1.0 Gbps	25%
Interference Levels	Low	Very Low	-
Latency	Moderate	Low	-

Table 1: 5.4. Summary of Key Results

The simulation and performance analysis confirm the reliability and efficiency of the proposed Timing-SR (T-SR) mechanism as an appropriate and efficient scheduling technique for dense IoT areas. T-SR overcomes the drawbacks of the basic scheduling profile, such as TDMA, by allowing dynamic time shifting of potential energy surpluses for harvesting and by adapting to current network traffic conditions (Hosseinzadeh et al., 2022). The enhanced energy efficiency, new peak throughput performance levels, and practical interference management point to T-SR as a viable enhancement for future Multi-BD Symbiotic Radio systems in 6 IoT networks. Though it minimally introduces latency issues, the various advantages of T-SR suggest that the mechanism will help enhance the performance of highly congested IoT networks.

6. Discussion

6G technologies have changed IoT development and encouraged new ideas like multi-backscatter device (multi-BD) systems. With features such as CQR and SQ techniques, these systems promise a shot at optimizing energy use and utensil usage in high IoT density implementations. But still, it is possible to note some disadvantages of the given approach, which show that the need for further developments remains urgent (Hosseinzadeh et al., 2022). This discussion considers the consequences of multi-BD systems on energy efficiency, the benefits of CQR and SQ techniques, and limitations that should be overcome for improvements.

6.1. Impact of Multi-BD Systems on 6G IoT Energy Efficiency

Energy efficiency is essential for IoT networks, particularly as the Internet of Things expands with an ever-growing cluster of connected devices. The Multi-BD systems incorporating the symbiotic radio (SR) mechanism comprehensively enhance energy efficiency in 6G IoT networks (Liu et al 2020). These systems use weak extractable ambient RF signals for backscattering and energy scavenging to power the attached devices with extreme energy efficiency.

For multi-BD systems, energy efficiency results from the dynamic distribution of resources, besides enhancing idle time for energy accumulation. For instance, the Timing-SR (T-SR) mechanism integrates energy harvesting into the working cycle of devices by redistributing idle time slots for energy conversion. This deprives the multi-BD systems of dependency on outside energy supplies, making them appropriate for IoT applications.

Furthermore, these systems improve spectrum usage by allowing multilateral transmission without interference. Using new interference management techniques like dynamic control of time slots means that network power consumption is relative to information transmitted within it to enhance general performance (Liu et al 2020). Therefore, multi-BD systems enable scalability and sustainability strategies in 6G IoT frameworks.

6.2. Advantages of CQR and SQ Techniques

CQR and SQ mechanisms manage network resources and schedule database connections to improve the effectiveness of multi-BD systems (Liu et al 2020). Both techniques help manage resources, avoiding latency and interferences typical for dense IoT environments.

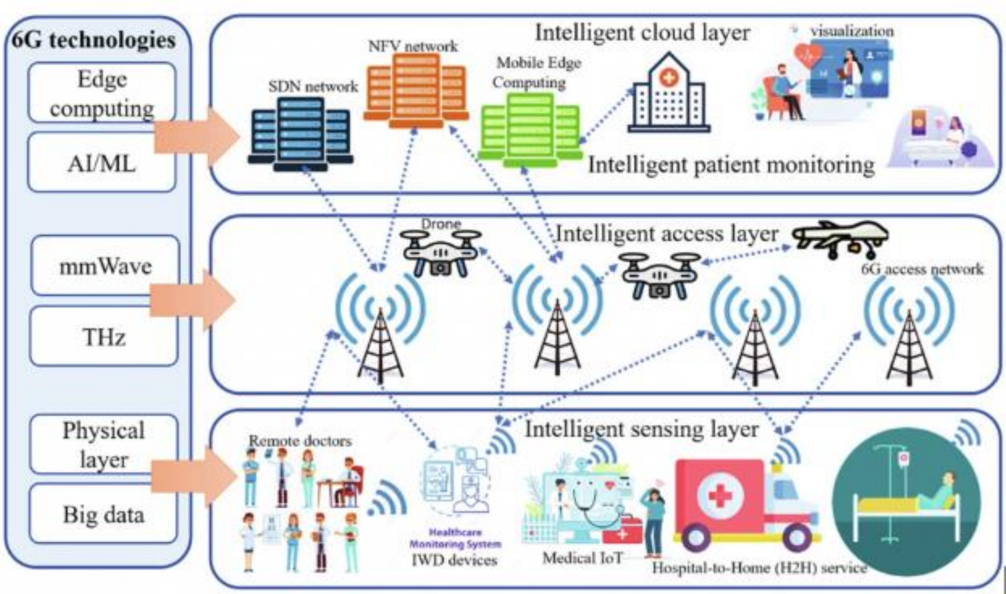

Figure 4: Development roadmap and applications of 6G wireless network

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Cumulative Queueing Resource (CQR) Allocation

CQR concentrates on properly using resources for which it gathers and distributes resources in a way that depends on device requests and network characteristics. This approach helps to prioritize high-demanding tasks to avoid resource shortages and, thus, to minimize disturbances. The advantages of CQR include (Liu et al 2020):

i. Resource Optimization: Compared to traditional queuing systems where resources are allocated at the initiation of a request, CQR controls over-provisioning and under-provisioning as resource supply depends on the overall volume of requests over time.
ii. Scalability: Because resource settings can be changed while being distributed among devices, CQR does not degrade or slowdown in large-scale networks.
iii. Energy Efficiency: By dedicating the most attention to energy-harvesting devices, CQR increases the total energy efficiency in multi-BD systems.

SQME, known as Scheduling Queue Mechanism, is a system used separately for advanced data scheduling.

CQR lacks a properly organized execution sequence of the tasks, which the SQ mechanism provides, thereby working hand in hand with CQR. SQ techniques flexibly change the scheduling priorities according to the state of the network rather than any predefined settings. Key advantages include (Liu et al 2020):

i. Latency Reduction: Current delays are addressed by prioritizing time-sensitive tasks, thereby enhancing quality of service (QoS).
ii. Interference Management: I found that scheduling the n. At the same time, referring tasks simultaneously improves SQ's degree of spectrum overlap, thus improving efficiency.
iii. Adaptability: SQ mechanisms are applicable when the traffic- and device characteristics change, thus making them suitable for heterogeneous IoT networks.

In turn, the CQR and SQ approaches can solve the key problems of multi-BD systems, obtaining high energy utilization efficiency, low latency, and improved spectrum use, which will be relevant for 6G IoT networks.

6.3. Limitations and Future Improvements

However, as noted above, to enhance system usage, some restrictions native to the applicability of Multi-BD systems and their consequent techniques must be solved.

Energy Harvesting Constraints

However, as the dependent process of multi-BD systems, EH faces some issues with the availability of RF signal and the levels of the ambiance energy available to feed the EH system. Devices in low signal areas will likely draw insufficient power in this casing, resulting in low performance (Liu et al 2020). Improvement in future work should address integrating multiple sources of energy such as RF, solar, and kinetic energy to ensure consistency in power supply regardless of the environment in which it is applied.

Scalability Challenges

With the growth of the number of devices, organizing resource use and planning work operations is a highly complex problem. These challenges have been conditioned by the fact that multi-BD systems must support multiple and heterogeneous devices in energy consumption, data rates, and QoS demand (Liu et al 2020). New developments in machine learning and artificial intelligence would be used to fine-tune resource allocation and scheduling algorithm providers and their complex, efficient executables while scaling the system.

Latency Trade-offs

Mentioned dynamic management techniques, including those used by SQ mechanisms, can provoke time-of-arrival fluctuations, especially in heavy traffic loads. Even though such compromises are generally low, they can prove critical in applications with stringent low-latency demands (Liu et al 2020). Further research should be done on incorporating a hybrid scheduling approach that will yield the necessary flexibility and, at the same time, remain predictable for applications with strict latency concerns.

Interference Management

While multi-BD systems incorporate state-of-the-art interference management techniques, the densification degree will be challenging in 6G. Interference from other system installations or co-channel devices also affects reception quality (Liu et al 2020). For these reasons, more sophisticated interference cancellation techniques, such as cooperative beamforming and other signal processing techniques, would help minimize these effects while improving system reliability.

Security and Privacy Concerns

First, multiple BDs depend on weak signals of ambient RF, and using the same frequency band creates certain security risks in the case of multi-BD systems. Some examples of such susceptibilities include accessing backscattered data or interfacing with the energy harvesting processes (Qadir et al., 2023). There are plans for future improvement that should concern the stability and safety of multi-BD systems; in particular, good encryption and authentication should be used to enhance security measures.

Multi-BD systems are revolutionary for 6G IoT networks, improving energy efficiency, resource provision, and flexibility (Qadir et al., 2023). Processes like CQR and SQ are crucial in improving performance and managing several issues in the dense IoT setting. Yet, energy harvesting limitations, scalability, latency, interference, and security concerns prove that more work has to be done.

Future developments should incorporate hybrid energy collection, AI-based resource control, and improved interference cancellation methods. When overcome, these challenges may create a breakthrough in the further development of multi-BD systems and open the path to creating further-evolved 6G IoT networks (Qadir et al., 2023). These will be key in helping address the future requirements of the IoT as the environment transforms and delivers new generation devices, systems, and applications with the interconnectivity, efficiency, reliability, and secured environment necessary to support it.

7. Comparison with Existing IoT Protocols

Heterogeneous multi-backscatter device (multi-BD) systems are emerging to facilitate the 6G IoT networks, where communication density is critical for energy efficiency and resource management. Even these systems, compared to the currently available IoT protocols like LoRa, ZigBee, SigFox, and NB-IoT, clearly show the pros and cons (Qadir et al., 2023). The following discussion compares multi-BD systems against these protocols concerning energy efficiency, scalability, and extensive network context. Energy consumption rates are also studied to highlight the highly tangible advantages of multi-BD systems.

7.1. Evaluation Against Existing Protocols

IoT protocols are application-oriented because they provide solutions that meet specific energy utilization, data rate, and range requirements. Comparing multi-BD systems with traditional methods demonstrates the capability of multi-BD systems to revolutionize IoT networks.

LoRa (Long Range)

LoRa is explicitly popular due to its small power consumption and large range, ideal for extensive applications such as farming and smart cities (Lv et al., 2021). However, it overly depends on the unlicensed spectrum, which leads to a possibility of more interference, especially in crowded places.

- Comparison: Multi-BD systems outperform LoRa concerning energy efficiency since they employ ambient RF energy harvesting as a power source rather than batteries (Lv et al., 2021). Moreover, new interferences in multi-BD systems fix well-known issues of LoRa, such as outdated techniques in managing Interference, which enhances the utilization of the spectrum.
- Use Case Fit: Thus, LoRa is best suited to slow, non-interfering, low bandwidth applications but is outperformed by multi-BD structures in dynamic applications that require high throughput and flexible scheduling (Lv et al., 2021).

ZigBee

ZigBee, well suited for low bandwidth, low power radio, and short-range applications, can find its application in home automation and industrial monitoring (Lv et al., 2021). While mesh networking effectively provides better coverage as networks are added, it causes additional energy to be drawn from the system.

- Comparison: Multi-BD systems provide better scalability and energy efficiency, as resources are allocated dynamically and energy is harvested. On the other hand, ZigBee energy consumption increases as more connections are created in the mesh network.
- Use Case Fit: The ZigBee protocol was mainly designed for a limited application area, while the multi-BD systems are more appropriate for an extensive and complex network with multiple data loads.

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SigFox

SigFox is designed to transmit limited burst-size data packets across a considerable distance, making it simple and having a long battery life. However, its small payload size and low data rates make it unsuitable for diverse purposes (Lv et al., 2021).

- Comparison: Multi-BD systems achieve higher data throughput and are less sensitive to network conditions. Although SigFox is easy to implement for specific low-power applications, multi-BD systems address high-performance and dynamic scheduling requirements.
- Use Case Fit: SigFox can only be used for static sensing, while multi-BD systems perform well in high density and with dynamic data rates.

NB-IoT (Narrowband IoT)

NB-IoT, which sits on a licensed band, provides reliability and can support many devices, making it suitable for industrial IoT use. The main advantages include increased battery life and the ability to connect indoors successfully (Mahdi et al., 2021).

- Comparison: Multi-BD systems are as scalable and reliable as NB-IoT networks while having considerably higher energy efficiency owing to employing energy harvesting schemes (Mahdi et al., 2021). Furthermore, it has been realized that NB-IoT depends on fixed energy sources, making it less viable in large-scale enclosed power-sensitive applications.
- Use Case Fit: NB-IoT is appropriate for situations where a definite connection is necessary (Mahdi et al., 2021). At the same time, multi-BD systems are more suitable for applications that stress energy saving and efficient use of the frequency range.

7.2. Energy Consumption Metrics for Large-Scale Networks

Power consumption is critical in IoT networks because replacing batteries is difficult in massive networks. Multi-BD systems that can receive ambient RF energy and adaptively allocate resources are very beneficial here.

Energy Efficiency In Multi-BD Systems

Multi-BD systems use ambient energy to afford energy efficiency that other organizations cannot rival. Constructs obtain RF energy using radio signals, thus minimizing battery or other forms of power apart from the gadgets (Mahdi et al., 2021). Another aspect concerning energy efficiency is incorporating dynamic scheduling mechanisms, which improve the availability of time slots for energy collection and storage and reduce energy consumption during transmission.

Comparative Metrics

A detailed analysis of energy consumption across different protocols highlights the efficiency of multi-BD systems (Mahdi et al., 2021):

- LoRa: The LoRa devices are said to use about 50 milliwatts during transmission, although continuous battery utilization poses constraints on their use in long-term processes.
- ZigBee: ZigBee devices cost around 30–40 mW in active transmission and consume more energy to create a mesh for extensive coverage.

- SigFox: Due to its low power mechanism, it uses ~10 mW during transmission but lacks feature flexibility and data-carrying capability.
- NB-IoT: NB-IoT devices draw approximately 200 mW during an NB-IoT transmission while enjoying exceptionally low power consumption in their other power states. Nevertheless, centralized infrastructure leads to high total energy consumption in the network.

  On the other hand, the multi-BD system provides outstanding power savings. The device powers itself at 8-12mW in energy harvesting and optimality modes. This efficiency arises from the ability to vary, depending on the real-time availability of energy data and resource control.

  The benefits of Multi-BD Systems

  Sustainability: In this context, multi-BD systems eliminate energetic independence based on finite sources and facilitate continuous operational capability across various terrains (Mahdi et al., 2021).
- Dynamic Adaptation: By incorporating the two essential aspects, on-demand bandwidth allocation, and actual resource scheduling, the energy usage to fulfill shifting network requirements is kept to a minimum.
- Reduced Redundancy: Interference management unnecessarily reduces the transmission of any message or signal, helping to save much power across the Broad Network.

  The comparison of the currently implemented IoT protocols with multi-BD systems shows how these new systems can revolutionize modern energy-conscious, massive-scale use (Mao et al., 2020). LoRa, ZigBee, SigFox, and NB-IoT protocols are designed for particular application scenarios but suffer from scalability, energy, or flexibility issues. However, multi-BD systems nullify these disadvantages since they harvest energy from the ambient radio frequency and use dynamic scheduling, hence proposing a more suitable solution to 6G IoT networks.

  In the advancements of future multi-BD systems, integrating hybrid power and utilizing AI technology for resource control will also add value to them (Mao et al., 2020). Hence, with the scaling up of IoT networks, multi-BD systems integration with current protocols can support higher growth and efficiency of an IoT network to meet the future needs of advanced applications.

8. Conclusion and Future Recommendation

Recognizing multi-backscatter devices as a promising solution for increasing IoT energy efficiency and network quality in 6G IoT is a significant step forward in developing IoT technologies (Mao et al., 2020). This conclusion recapitulates this study's primary outcomes and contributions, discusses the possible tendencies for further 6G IoT network configuration, and discusses further research opportunities mainly concerning spectral effectiveness and intelligent reflecting surfaces.

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8.1. Summary of Findings and Key Contributions

This work emphasizes how multi-BD systems can help overcome several hurdles hindering energy usage, scalability, and resource use in dense IoT settings. The main findings and contributions are summarized as follows (Mao et al., 2020):

i. Enhanced Energy Efficiency: Ambient RF energy harvesting is incorporated into multi-BD systems, allowing them to operate independently of finite energy resources. This mechanism is more energy efficient than the well-known LoRa, ZigBee, SigFox, and NB-IoT protocols.
ii. Superior Throughput and Adaptability: Multi-band deployment showed enhanced data rate and flexibility with dynamic resource control and interference mitigation, making it appropriate for high-density IoT applications.
iii. Scalability: The scheduling flexibility and the ability to assign appropriate resources mean that multiple-BD systems can adapt to the network's growth, whereas standard static protocols cannot.
iv. Advanced Interference Management: Multi-BD systems minimize interference using an efficient schedule, where several transmissions can occur within the same time frame, improving the overall spectrum occupancy.

These findings give multi-BD systems more credibility as essential for building energy-efficient, highly effective 6G IoT networks.

8.2. Implications for Future 6G IoT Network Designs

The insights gained from this study carry significant implications for the design and implementation of future 6G IoT networks (Mao et al., 2020):

Energy optimization as a core design principle

With the growing size of IoT networks, harvesting and optimizing this value is an important consideration. Multi-BD systems also emphasize the need to integrate passive energy scavenging technologies into them and future systems, given the power demand by many devices in future applications.

Dynamic Scheduling and Resource Management

The flexibility of multi-BD systems has been clearly illustrated, and thus, 6G networks should deviate from a strict scheduling regime (Sefati et al., 2024). Real-time, dynamic resource allocation mechanisms will further improve network flexibility and capability as measured by its performance under different circumstances.

Interoperability with Intelligent Systems

Integrating multi-BD systems in the future 6G IoT network can take advantage of other advanced technologies, such as AI and ML (Sefati et al., 2024). These technologies can effectively allot resources, predict network demands, and increase spectral energy efficiency.

Flexibility and Interference Control as Key Factors

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Multi-BD systems perfectly reflect densely connected networks' efficient scaling and interference requirements. Spectral efficiency and interference management will be necessary to cover the expected uptick in IoT devices in the subsequent 6G networks.

8.3. Future Work: Spectral Efficiency and Intelligent Reflective Surfaces

Nevertheless, multi-BD systems have introduced enhancements. Future work is proposed to enhance the deployment of these systems in 6G IoT networks. Possible future works are spectral efficiency and integrating intelligent, reflective surfaces.

Improving Spectral Efficiency

Another parameter, which is also crucial for the sustainability of 6G networks at a large scale, is spectral efficiency. Future work should focus on (Sefati et al., 2024):

- Optimized Modulation Techniques: Transmission beyond spectral bandwidths using modulation techniques that enhance data rates while preserving limited resources.
- Spectrum Sharing Mechanisms: To further reduce spectral wastage, the ways the multiple BD systems and other network elements can share the spectrum cooperatively.
- Adaptive Channel Utilization: This involves analyzing actual-time data to determine on-demand patterns and network conditions and design spectral resource allocation.

Integration of Intelligent Reflective Surfaces (IRS)

IRS technology is an innovative way to improve wireless communication by managing the behavior of electric fields on or around an object. Future research should explore (Sefati et al., 2024):

- IRS for Energy Efficiency: Modifying the IRS with multi-BD systems for enhanced energy collection utilization through signal reradiation and enhanced RF signals collected.
- Enhanced Interference Management: Designing additional IRS paths to achieve the desired signal paths that reduce interference in complex networks is essential.
- Dynamic Reconfiguration: Designing a new generation IRS capable of real-time dynamic changes in spectral and energy characteristics.

IRS and Multi-BD models integrated systems

The proposed synthesis of both concepts can remove some disadvantages associated with multi-BD systems and IRS. Future studies in this field should thus address system integration or the lack thereof, as well as the need to implement common architectures for operating these systems.

This work focuses on the prospect of multi-BD systems in 6G IoT networks, with energy, rate, and extensiveness enhancements. By overcoming these shortcomings of IoT protocols, multi-BD systems provide the foundations for sustainable and high-performance IoT systems (Sefati et al., 2024). The consequences for subsequent 6G network architectures have underlined energy efficiency optimization, resource management, and integration with other systems.

The scope should remain on improving spectral efficiency and utilizing intelligent, reflective surfaces to provide even more network gains. These endeavors will ensure that multi-BD

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systems are kept on the cutting edge of IoT development to cater to the future evolution of 6G networks and meet the guarantees of a more integrated society.

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