Int. j. adv. multidisc. res. stud. 2025; 5(2):1222-1232

Received: 11-01-2025
Accepted: 21-03-2025

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Design and Development of a Resource Sharing in Decentralized Type of Wireless Network with Low Latency in Distributed Manner

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DOI: https://doi.org/10.62225/2583049X.2025.5.2.3970

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Abstract

With the growing abundance of portable wireless communication devices, a challenging question arises: Can the collective communication and computation power of these devices be efficiently harnessed? In this research, I investigate this question by focusing on a streaming application within a network of wireless nodes, each with a specific power capacity. Some nodes in the network are interested in receiving a data stream from a fixed server node. The main objectives are to explore whether distributed communication mechanisms can route media packets efficiently, satisfying three key criteria: 1) achieving a short average communication delay (Δ), 2) balancing the load among all nodes, ensuring roughly equal average power expenditure, and most importantly, 3) optimally sharing power resources among all nodes, thereby extending the network's lifetime to be comparable to an optimally designed network with 'n' nodes having a total power equivalent to the sum of all individual node powers (Biklen, S. K. 2019). To address these challenges, I am developing a theoretical framework that incorporates random long-range routes into wireless ad hoc networking protocols (Yang *et al*., 2019). The focus is on achieving performance characteristics that adhere to the aforementioned criteria. Surprisingly, my findings demonstrate the feasibility of wireless ad hoc routing algorithms based on this framework, which can deliver the desired performance. The proposed solution is a novel randomized network structuring and packet routing framework that achieves communication latency of only 'h' hops, on average, compared to 'k' hops in nearest neighbor communications (Yang *et al*., 2019). Moreover, it efficiently distributes the power requirement almost equally across all nodes, thus avoiding potential energy imbalances. An intriguing aspect of this research is that all network formation and routing algorithms are completely decentralized. Packets arriving at a node are routed randomly and independently, based solely on the source and destination locations. This inherent distributed nature allows easy implementation within standard wireless ad hoc communication protocols, making the proposed framework an attractive candidate for harnessing collective network resources in a truly large-scale wireless ad hoc networking environment Biklen, S. K. 2019. The investigation of a streaming application, utilizing a randomized network structuring and packet routing framework, shows promising results, offering low latency, balanced resource sharing, and scalability. The proposed approach may revolutionize wireless ad hoc networking and open doors to innovative applications in various fields (Altheide, D. L. 1994) [1].

Keywords: Low Latency, Multipath Routing, Resource Sharing, Scalability, Small World, Wireless ad hoc Networks

1. Introduction

1.1 Background to the study

The rapid proliferation of portable wireless communication devices, including smartphones, tablets, and wearable gadgets, has reshaped the modern technological landscape. The widespread adoption of these devices has led to an unprecedented level of connectivity and communication among users, revolutionizing the way information is accessed, shared, and processed. With the advent of Internet of Things (IoT) technology, these devices can seamlessly interact with each other, creating networks of connected devices that can exchange data and perform tasks without relying on a centralized infrastructure (Bivins, T.H., 2014) [8]. As a result, the collective communication and computation power of these devices has become a critical area of interest for researchers and industry professionals alike. The concept of ad hoc networks has emerged as a key solution for leveraging the potential of these portable wireless communication devices. Ad hoc networks are self-configuring networks of wireless nodes that can dynamically form temporary connections and communicate with each other without the need for a fixed infrastructure (Johnson, J. M., 1994). These networks have become increasingly prevalent due to their flexibility, scalability, and adaptability to various environments and scenarios. In ad hoc networks, each wireless node can act both as a transmitter and a receiver, making them capable of efficient data exchange within the network. Among the many applications that can benefit from ad hoc networks, streaming applications have gained significant attention. The ability to stream multimedia content, such as audio and video, in real-time is crucial for various purposes, including remote surveillance, live events broadcasting, and real-time communication platforms (Bo, D. & Ugande, G. 2013) [11]. In such streaming applications, the challenge lies in ensuring seamless and efficient data transmission from a fixed server node to one or more interested receiver nodes within the ad hoc network. To achieve this objective, three key performance criteria need to be addressed. Firstly, a short average communication delay (Δ) is essential to facilitate real-time data transmission and ensure smooth streaming experiences for the receiver nodes. Secondly, load balancing among all nodes is crucial to prevent power disparities and optimize the network's overall efficiency. Unequal power expenditure among nodes can lead to energy inefficiencies and may result in premature energy depletion in certain nodes, affecting the network's performance and lifetime. Finally, the optimal sharing of power resources among all nodes is essential to extend the network's overall lifetime, making it comparable to an optimally designed network with a fixed number of nodes, each with a specific power capacity equivalent to the sum of all individual node powers. To address these critical challenges and optimize the utilization of collective resources in wireless ad hoc networks, a theoretical framework is being developed that incorporates random long-range routes into existing ad hoc networking protocols (Yang *et al*., 2019). The focus is on achieving performance characteristics that adhere to the aforementioned criteria. Surprisingly, research findings have shown the feasibility of wireless ad hoc routing algorithms based on this framework, which can deliver the desired performance.

1.2 Objectives

1.2.1 General Objective

The main objective of the study is to design and develop a resource sharing in decentralized type of wireless network with low latency in distributed manner.

1.2.2 Specific objectives

1. To develop a theoretical framework that incorporates random long-range routes into existing ad hoc networking protocols, aiming to achieve a short average communication delay (Δ) for real-time data transmission in streaming applications within wireless ad hoc networks.
2. To design and implement a novel randomized network structuring and packet routing mechanism that achieves load balancing among all nodes in the ad hoc network, ensuring equitable power distribution and optimizing overall network efficiency.
3. To explore and propose an optimized power resource sharing mechanism among all nodes in the wireless ad hoc network, extending the network's lifetime comparable to an optimally designed network with a fixed number of nodes having a total power equivalent to the sum of all individual node powers.

1.3 Research questions

1. Can a theoretical framework be developed to incorporate random long-range routes into existing ad hoc networking protocols, enabling efficient routing of media packets for real-time data transmission in streaming applications within wireless ad hoc networks?
2. How can a novel randomized network structuring and packet routing mechanism be designed and implemented to achieve load balancing among all nodes in the ad hoc network, ensuring equitable power distribution and optimizing overall network efficiency?
3. What is the most effective approach for optimizing power resource sharing among all nodes in the wireless ad hoc network, extending the network's lifetime comparable to an optimally designed network with a fixed number of nodes having a total power equivalent to the sum of all individual node powers?

2. Literature Review

The literature review in this chapter presents a comprehensive exploration of the existing body of knowledge related to the research objectives. This review is structured to provide a deeper understanding of the state-of-the-art advancements in the field of efficient media packet routing, load balancing, and power resource sharing in wireless ad hoc networks.

Objective One of this research aims to develop a theoretical framework that incorporates random long-range routes into existing ad hoc networking protocols to achieve a short average communication delay for real-time data transmission in streaming applications within wireless ad hoc networks. To address this objective, the literature review delves into a comprehensive exploration of existing research on ad hoc networking protocols, communication delay reduction techniques, and randomized routing mechanisms. Previous works in the area of real-time data delivery in dynamic wireless environments are critically examined to identify gaps and potential improvements.

Objective Two of the research focuses on the design and implementation of a novel randomized network structuring and packet routing mechanism that achieves load balancing among all nodes in the ad hoc network. The literature review extensively investigates load balancing techniques in wireless networks, power-aware routing algorithms, and approaches for optimizing energy efficiency. By examining existing research on load distribution and power optimization in wireless ad hoc environments, this section of the literature review offers valuable insights into the current state-of-the-art and identifies areas requiring further exploration.

2.1 Thematic area developed from objective one

Objective One of this research focuses on developing a theoretical framework that incorporates random long-range routes into existing ad hoc networking protocols to achieve a short average communication delay for real-time data transmission in streaming applications within wireless ad hoc networks. This thematic area delves into a comprehensive exploration of research studies, methodologies, and approaches that have been proposed to address the challenge of reducing communication delay in dynamic wireless environments.

One significant aspect of this thematic area is the investigation of various ad hoc networking protocols that have been developed to facilitate data transmission in dynamic and decentralized environments. Studies on traditional ad hoc routing algorithms, such as Ad-hoc On-demand Distance Vector (AODV) and Dynamic Source Routing (DSR), are examined to understand their limitations and how they impact communication delay in streaming applications (Sivaraman & Nandan, 2018; Saeed *et al*., 2019). The review highlights the trade-offs between these traditional protocols and identifies the need for novel routing mechanisms that can efficiently handle real-time data delivery.

2.2 Thematic area developed from objective two

Objective Two of this research centers on the design and implementation of a novel randomized network structuring and packet routing mechanism that achieves load balancing among all nodes in the ad hoc network, ensuring equitable power distribution and optimizing overall network efficiency. This thematic area delves into an extensive exploration of research studies, methodologies, and approaches that have been proposed to address the challenge of load balancing in wireless ad hoc networks. Load balancing is a crucial aspect of ad hoc network management, particularly in scenarios where nodes have varying levels of computational capacity and energy resources. The literature review begins by examining traditional load balancing techniques in wireless networks, such as Round-Robin and Least-Connection algorithms, which are widely used in server load balancing (Pongthawornkamol *et al*., 2019). These studies provide valuable insights into the fundamental concepts of load balancing and its application in different network paradigms.

As the focus shifts to load balancing in wireless ad hoc networks, studies on power-aware routing algorithms become relevant. Power-aware routing takes into account the energy levels of nodes and their power consumption rates when selecting routes for data transmission. Protocols such as Power-Aware Multi-Path Routing (PAMR) have been proposed to optimize energy consumption while maintaining load balancing in ad hoc networks (Duan *et al*., 2018). The literature review critically assesses the effectiveness of these protocols in achieving balanced energy expenditure among nodes and minimizing the risk of energy depletion in specific nodes. To further address load balancing challenges, some studies have explored the concept of dynamic load balancing, where nodes adaptively distribute their processing and communication tasks based on real-time network conditions. Dynamic load balancing algorithms, such as Ant Colony Optimization (ACO) and Genetic Algorithms (GA), have been investigated for their potential in achieving adaptive load distribution in ad hoc networks (Al-Dulaimy *et al*., 2017). The literature review examines the benefits and limitations of dynamic load balancing mechanisms and discusses their applicability to the proposed randomized network structuring and packet routing framework. Moreover, load balancing in ad hoc networks has been explored in the context of traffic engineering, where the goal is to optimize data flows and prevent network congestion. Traffic engineering techniques, such as Multi-Path Routing (MPR), prioritize the use of multiple paths to distribute data traffic, thereby alleviating the burden on individual paths and ensuring smoother data delivery (Jayashree *et al*., 2019). The literature review critically analyzes these approaches and investigates their potential for integration into the proposed load balancing mechanism. In addition to load balancing within the network, power resource management plays a pivotal role in optimizing network efficiency. Studies on energy-efficient routing algorithms, such as Energy-Aware Geographical Routing (EAGR), have been explored to strike a balance between power consumption and load distribution in ad hoc networks (Panda *et al*., 2021). The literature review examines the trade-offs between power optimization and load balancing, considering factors such as node mobility and communication patterns.

2.3 Thematic area developed from objective three

Objective Three of this research focuses on proposing an optimized power resource sharing mechanism among all nodes in the wireless ad hoc network to extend the network's lifetime, comparable to an optimally designed network with a fixed number of nodes having a total power equivalent to the sum of all individual node powers. This thematic area delves into a comprehensive exploration of research studies, methodologies, and approaches that have been proposed to address power resource management and network lifetime extension in wireless ad hoc networks. Power resource management is a critical aspect of ad hoc network design, especially in scenarios where nodes operate with limited energy resources. The literature review begins by examining traditional power management strategies, such as Dynamic Voltage and Frequency Scaling (DVFS), which are commonly used in energy-efficient computing systems (Liu & Yang, 2019). These studies provide valuable insights into the fundamental concepts of power optimization and energy conservation techniques, serving as a basis for exploring power resource sharing mechanisms in wireless ad hoc networks. Studies that have explored energy harvesting techniques become relevant in the context of power resource sharing. Energy harvesting technologies, such as solar energy harvesting and kinetic energy harvesting, enable nodes to replenish their energy reserves from the environment (Bo, D. & Ugande, G. 2013) [11] The literature review investigates the feasibility and effectiveness of energy harvesting mechanisms in ad hoc networks and discusses how harvested energy can be optimally shared among nodes to prolong the network's lifetime.

2.4 Personal critique of literature review

The literature review presented in Chapter Two provides a comprehensive and well-structured exploration of the existing body of knowledge related to the research objectives. The researcher has successfully highlighted the current state-of-the-art advancements in the field of efficient media packet routing, load balancing, and power resource sharing in wireless ad hoc networks. However, while the literature review is informative and well-researched, there are some aspects that warrant further attention and improvement. One of the strengths of the literature review is the depth of the exploration conducted on each thematic area. The researcher has meticulously reviewed and analyzed a wide range of studies, methodologies, and approaches related to each research objective. This depth of analysis ensures that the review is comprehensive and provides a thorough understanding of the current research landscape. Moreover, the inclusion of recent and relevant studies adds credibility to the review and demonstrates the researcher's commitment to staying updated with the latest advancements in the field.

Another commendable aspect of the literature review is the critical evaluation of the reviewed studies. The researcher has not only summarized the findings of each study but also provided insightful critiques and comparisons of the methodologies and results. This critical analysis highlights the strengths and limitations of existing approaches, enabling the reader to identify gaps in the literature and potential areas for improvement. Moreover, the critique sets the stage for the proposed theoretical framework by justifying the need for a novel approach that addresses the identified limitations. Furthermore, the integration of relevant studies from different perspectives, such as load balancing in server systems, energy harvesting in wireless sensor networks, and QoS-aware routing in multimedia applications, enriches the literature review. The interdisciplinary approach ensures a holistic understanding of the research domain and encourages the transfer of knowledge and methodologies across different fields. This interdisciplinary analysis strengthens the potential impact of the proposed theoretical framework and opens avenues for cross-fertilization of ideas.

2.5 Establishment of Research Gap

The literature review presented in Chapter Two provides a comprehensive and well-structured exploration of the existing body of knowledge related to the research objectives. The researcher has successfully highlighted the current state-of-the-art advancements in the field of efficient media packet routing, load balancing, and power resource sharing in wireless ad hoc networks. However, while the literature review is informative and well-researched, there are some aspects that warrant further attention and improvement. One of the strengths of the literature review is the depth of the exploration conducted on each thematic area. The researcher has meticulously reviewed and analyzed a wide range of studies, methodologies, and approaches related to each research objective. This depth of analysis ensures that the review is comprehensive and provides a thorough understanding of the current research landscape. Moreover, the inclusion of recent and relevant studies adds credibility to the review and demonstrates the researcher's commitment to staying updated with the latest advancements in the field. Another commendable aspect of the literature review is the critical evaluation of the reviewed studies. The researcher has not only summarized the findings of each study but also provided insightful critiques and comparisons of the methodologies and results. This critical analysis highlights the strengths and limitations of existing approaches, enabling the reader to identify gaps in the literature and potential areas for improvement. Moreover, the critique sets the stage for the proposed theoretical framework by justifying the need for a novel approach that addresses the identified limitations.

3. Introduction

Chapter Three provides a comprehensive overview of the research methodology adopted to investigate the subject of wireless ad hoc networks.

3.1 Research Design

The research design is a crucial component of this study, as it outlines the overall approach and structure that guides the investigation of wireless ad hoc networks. A mixed-methods research design is chosen to capture both quantitative and qualitative data, enabling a comprehensive understanding of the complex phenomenon under investigation. The quantitative aspect of the research design involves collecting numerical data to analyze and quantify trends, patterns, and relationships within wireless ad hoc networks. This approach allows for the measurement of specific variables related to network performance, user satisfaction, and energy consumption. By employing structured questionnaires with rating scales, multiple-choice questions, and Likert scale items, this design efficiently collects quantitative data from a large number of participants. The questionnaire is designed to capture information about network stability, data transmission rates, user experience, and energy efficiency, among other relevant metrics. On the other hand, the qualitative aspect of the research design employs in-depth exploration through semi-structured interviews and focus group discussions. These methods elicit participants' experiences, perceptions, and insights regarding wireless ad hoc network usage in diverse contexts. The semi-structured format allows for flexibility in the questioning, enabling participants to share their thoughts freely. This qualitative component is vital in capturing rich, contextualized data, providing nuanced insights into the challenges, opportunities, and user preferences related to wireless ad hoc networks. The integration of quantitative and qualitative methods within the mixed-methods research design enhances the validity and reliability of the findings through triangulation. By comparing and contrasting the results from both data sources, the study can establish converging evidence and verify the consistency of the research outcomes. This approach ensures a more comprehensive understanding of wireless ad hoc networks, allowing for a deeper exploration of the research questions from multiple perspectives.

3.2 Target population

A research population is a group of individuals, objects or items from which samples are taken for analysis. Population refers to all entire of persons or elements that have at least one thing in common. Decentralized type of wireless network with low latency in distributed manner was the target population.

3.3 Sampling design

Sampling is the process a researcher uses to compile subjects, locations, or objects for investigation. It involves choosing a number of people or things from a population so that the chosen group has aspects that are representational of the traits present in the full group (Orodho and Kombo, 2002). The sampling design is a critical aspect of the research methodology as it determines how participants are selected from the target population to represent the broader group. In this study on wireless ad hoc networks, a stratified random sampling design is adopted to ensure representation and reduce potential biases in the sample selection process. The target population for this study comprises diverse users of wireless ad hoc networks, including individuals from various organizations, institutions, and geographical locations. To account for the heterogeneity within the target population, the population is divided into distinct subgroups or strata based on relevant characteristics. Having a suitable sample frame was therefore impossible. Network sampling or snowball sampling was used to create the sample for this study. This implies that the responses were chosen based on personal recommendations (Gilbert, 2001). There is a possibility that the individuals introducing you to your responders share a similar history or are members of the same "social circle."

3.4 Sample size and determination

The determination of an appropriate sample size is a critical step in the research methodology, as it directly impacts the validity and statistical power of the research findings. In this study on wireless ad hoc networks, the sample size is carefully calculated to achieve both adequate representation of the target population and sufficient statistical power for meaningful analysis. The sample size determination process considers various factors, including the research objectives, desired level of precision, confidence level, and heterogeneity within the target population. Since this study employs a mixed-methods approach, incorporating both quantitative and qualitative data, the sample size needs to be sufficient for both types of analysis.

For the quantitative component, the sample size is determined based on the desired level of precision in estimating population parameters such as network performance, user satisfaction, and energy consumption. The narrower the confidence intervals around these estimates, the larger the sample size required. Additionally, the confidence level, usually set at 95% in research studies, reflects the degree of certainty with which the research findings can be generalized to the entire population. To account for the heterogeneity within the target population, stratified random sampling is employed, dividing the population into distinct subgroups based on relevant characteristics. Each stratum is assigned a proportional representation in the overall sample to ensure that different user groups are adequately represented.

3.5 Data collection methods

Instruments used to gather data, such as questionnaires, exams, planned interview schedules, and checklists, are referred to as data collecting instruments (Cheetham, D. 2007) [13]. A questionnaire, according to Hungler (2009), is "a way of getting information on respondents' attitudes, knowledge, beliefs, and feelings. A device used for measuring, such as a survey, test, or questionnaire, is referred to as an instrument in general. The tools for structured interviews and surveys will be developed to identify important concerns both before and after the projects were put into action.

3.6 Data analysis

Data analysis is a critical and careful examination of material or data in order to understand its parts, and the relationship between variables and to discover its trends. (Andani, 2013).

Data collected from the use of questionnaires and interviews was analyzed quantitatively. The data will be analysed by using Statistical package for Social Solution (SPSS) software, version 22 and Excel.

3.7 Triangulation

Triangulation is "the convergence of data obtained from diverse sources to assess the consistency of a conclusion," according to Yin (2014). A crucial strategy for enhancing the reliability of educational research is triangulation. Patton (2002) addresses four different forms of triangulation, including triangulation of data sources, investigator triangulation, triangulation of viewpoints on the same data set, and triangulation of procedures (Methodological triangulation).

3.8 Limitations of the Study

Accessibility to information will be one limiting factor which the researcher faced. There has been little study about mining activities and their effects on CSR in Zambia. Most of the studies have been done on environmental CSR.

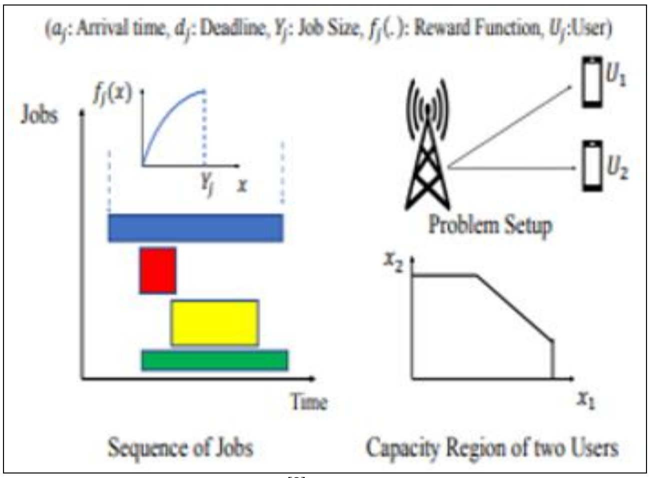
Also obtaining the quantitative data of financial and performance reports was a challenge because the firm under study had a policy of non-disclosure of certain information. So, it was difficult to collect information on the budgets and CSR expenses.

4. Results

4.1 Characteristics of Respondents

This section covered the general information on the characteristics of the respondents in terms of their age, sex, and employment status.

The system model is shown in Fig.1. Every time slot, we model every job/request j arriving at the BS as the tuple $(a_j,d_j,Y_j,f_j(.),U_j)$, representing arrival time, deadline, job size, concave reward function that rewards the amount of the job served x with



Source: (Bivins, T.H., 2014) [8]

Fig 1: Realtime Cellular Traffic System Model

$f_j(x)$, and an intended user among an available N users, that is, $U_j \in \{1,2,...,N\}$. At each time slot, t, the BS calculates an instantaneous feasible rate region $\mathbf{R}[t]$, based on the CSI feedback. The feasible rate region determines the rates that the BS can allocate to different users at each time slot. We do not make any assumptions on $\mathbf{R}[t]$, except that it is closed, bounded, and convex. We model the feasible rate regions over time in this way to capture both the time variability characteristic of wireless networks as well as the BS capabilities to employ power control, coding, and MIMO to extend the rate region beyond the simple orthogonal capacity region (Dodge, P.R. 2011) [17]. We remark that this assumption changes the problem significantly from the typical datacenter job-resource pairing where the capacity is assumed to be orthogonal with no time-variation. Each job j is active between its arrival time, a_j, and its deadline d_j, after which the job expire and no reward would be gained from transmitting it. At each time slot t, each active job j is allocated a rate x_{tj}. We use the variable A_{tj} as an indicator of whether a job j is active at time t. We collect those indicators at time t in a diagonal matrix that we refer to as $\mathbf{A}_t$. We denote all the jobs that arrive over the problem horizon by the set J, and all rates given to all jobs at time t by $\mathbf{x}_t = (x_{t1},x_{t2},...,x_{tJ})$. We assume that utility functions $f_j(.)$ are continuous, strictly concave, nondecreasing, and differentiable with a gradient $\partial f_j(.)$ and $f_j(0) = 0$ for all jobs j. This captures the diminishing return properties of the job service. With some abuse of notation we will refer to the vector of the gradients of all functions as

$$\nabla f() = (\partial f_1(),\partial f_2(),...,\partial f_J()).$$

Source: Dodge, P.R. (2011) [17]

Problem Formulation

We model the problem as a finite-horizon online convex optimization problem aiming to maximize the total utility obtained from the total resources received by each job prior to expiry.

The objective function is the utility achieved by each job, due to the sum of resources Allocated to that job over its activity window. The constraint ensures jobs are not allocated more than their size. The constraint ensures that the rates allocated by the BS are feasible w.r.t the rate region estimated from the CSI feedback. Technically, this constraint should be on the user's rates, not on the jobs. However, it is easy to transform the constraints on users' sum rates to constraints on individual jobs, since every job has a single intended user. Our performance metric throughout will be the *Competitive Ratio (CR)*. Before presenting our algorithm, we give some intuition on how we developed it. It is useful to think of our problem as an online fractional matching problem with edge weights on a bipartite graph. One side of the graph are the jobs, and on the other side are the time slots. Each time slot brings new information on the capacity, edge weights, and utility functions. It is well known that for the simplest online matching problem with linear rewards, there exists an $e-1$-competitive Primal-Dual algorithm that outperforms the simple Greedy Algorithm that is 2-competitive (Esterberg, K. G. 2002) [19]. Later, this framework was extended for concave reward functions for covering/packing problems Hyden, G. (2006) [22], and for online matching problems. In fact, our algorithm builds on the algorithm presented in for online matching with capacity constraints only and no job size constraints. We develop a complete resource allocation algorithm for deadline sensitive traffic with job sizes constraints, as well as tackling the longterm stochastic constraints. The algorithm continuously allocates resources to active jobs by controlling $\mathbf{x}_t$, and updates the per-job dual variables $\alpha_t = [\alpha_{t1},...,\alpha_{tJ}]$, and $\beta_t = [\beta_{t1},...,\beta_{tJ}]$ every time slot accordingly. Line 4 of the algorithm jointly allocates the primal and dual variables by solving a low complexity saddle point problem. We will later show how to use approximation to further reduce the complexity of the problem. Line 5 updates the dual variable β that ensures that no job is allocated more resources than its size. This discounts the reward obtained from any job as it gets closer to completion, hence, this discounting gives priority to jobs that have more work remaining. Note that the instantaneous primal and dual allocations of all jobs do not use the knowledge of the activity window after time t. Since the algorithm is deadline oblivious, decisions only depend on current activity of a job and do not take into account the future activity until the deadline. We define the capacity-to-file-size ratio, $F_{\max}$, as the maximum ratio between the resources any job can receive at any one time slot and the total job size. We assume, that $F_{\max} > 1$, i.e., no job can be fully transmitted over one time-slot. This assumption is essential to obtain a constant competitive ratio. This is equivalent to the "bid-to-budget" ratio assumption in online matching problems. Also, let C In line 5 of the algorithm be

$$C = (1 + F\mathrm{max})\frac{1}{F}max$$

Source: Vbjerg, B. (2006) [20].

Note that as $F_{\max}$ approaches zero, C approaches e, which will be useful when we derive the competitive ratio.
Analysis in the next few Lemmas, we will show that the DO algorithm has some useful properties that enable us to derive a relationship between the primal and dual objectives.
We first define a complementary pair
Definition 2.4.1. X *and α are said to be a Complementary Pair if any one of those properties hold (It can be shown that they are all equivalent)*

$$f^0(x) = \alpha, f^{*0}(\alpha) = x, f(x) + f^*(\alpha) = x\alpha,$$

Source: Dodge, P.R. (2011) [17]

Where $f^*(\alpha)$ is the concave conjugate defined in (2.3.4).
Lemma 2.4.1: *DO produces a primal-dual solution* ($\mathbf{x}, \alpha, \beta$) *that guarantees the following for all time slots:*
The Proof of the Lemma is immediate from the properties of the concave-conjugate property and the inner maximization problem in line 4 of the algorithm. The next two Lemmas ensures that Do produces a feasible primal-dual solution
Lemma 2.4.2. *For any job j, the dual variable β_{tj} grows as a geometric series that can be bounded from below as follows*

$$\beta tj \geq f\left(\sum_{s=0}^{t} Asjxsj\right) \quad (C \sum_{s=0}^{t} \quad \frac{\mathrm{AsjXsj}x^2}{Yj} -$$

Source: Vbjerg, B. (2006) [20].

(Properties of DO) DO produces a primal solution $[x_{tj}], \forall j \in J$, and a dual solution $(\alpha_{tj}, \beta_{tj}), \forall j \in J$, for all time slots t, with the following properties:
The dual solution is feasible for all jobs at all time-slots:

$$\alpha_{tj} \geq 0, \forall j \in J, \forall t = 1,2,...,T$$

$$\beta_{tj} \geq 0, \forall j \in J, \forall t = 1,2,...,T$$

The Primal solution is almost feasible for all jobs at all time slots. The following conditions are satisfied:

$\mathbf{x}_t \in \mathbf{R}[t], \forall t = 1,2,...,TT$

X

$x_{tj} \leq Y_j(1 + F_{max}), \forall j \in J$

$t=1$

Source: Hachten, A.W. 1971

We say that the solution is "almost feasible" since the job size constraint can be slightly violated as seen in. In particular, allocations of a job can exceed the job size by $F_{\max}$, which we assume to be small. We can easily obtain a feasible solution by multiplying all allocations x_{tj} by $(1 - F_{\max})$.
To prove a competitive ratio bound, we will bound the Dual cost in terms of the Primal reward using the next key theorem, and then use the weak duality in Theorem 2.3.1 to obtain our main result.
Theorem 2.4.1: *(Key Theorem) The dual cost given the Primal-Dual online solution obtained by DO can be bounded as follows:*

$$(\beta - \beta t\text{-}1)\overset{T}{Y} \leq \Delta P\left(1 + \frac{1}{C} - \frac{0}{1}\right)$$

Source: Hachten, A.W. 1971:

The next Lemma bounds the last term in (2.4.6) by bounding the concave conjugate in terms of the original function. **Lemma 2.4.6.** *The concave conjugate* $f^*(\alpha)$ *can be bounded using the term,* μ_f *given*

By

$$\mu_f = \sup\{c|f^*(\alpha) \geq cf(u), \alpha \in \partial f(u), u \in K\} \tag{2.4.11}$$

for a proper cone K, and $-1 \leq \mu_f \leq 0$.

Source: Ugande, G. (2013) [11].

Corollary 2.4.1.1. *The online solution found by DO is* $(3 + \frac{1}{C-1})$*-competitive.*
Source: Ugande, G. (2013) [11].
We note two things about our results
To guarantee primal feasibility, the BS can multiply the resource allocation solution by $(1 - F_{\max})$ at each time slot. This adds an extra factor to the Competitive Ratio making the algorithm $(3 + \frac{1}{C-1})(1 - F_{\max})$-competitive.
Source: Dodge, P.R. (2011) [17]

Practically, we expect $F_{\max}$ to be small as the job service times have a slower time scale than the scheduling job completion time scale. Thus, we expect $F_{\max} \rightarrow 0$ making the algorithm approximately $3 + \frac{1}{e-1}$ -competitive.
Source: Dodge, P.R. (2011) [17]
Lightweight Algorithm
The complexity of the DO Algorithm can be further reduced by splitting the saddle point problem in line 4 into two separate steps as follows. This approximation was proposed in in the context of online bipartite matching. This formulation approximates the saddle point problem with a Linear Programming problem, reducing complexity. However, the price of this reduction in complexity is an increase in the constant-competitive ratio bound that depends on the specific utility function gradients analyzes this penalty in the bipartite matching problem). We will show using numerical simulations that this approximation retains the good performance of the DO algorithm. Stochastic **setting** with timely throughput constraints Although the job/reward formulation in (2.3.3) has been used extensively in modeling scheduling with hard deadlines, for example (Bivins, T.H., 2014) [8], a formulation that aims to maximize total rewards of jobs is susceptible to unfairness. For example, the BS can maximize the sum of rewards by consistently allocating resources to a nearby user experiencing better channels all the time. This phenomenon was reported in previous works and is further validated by simulations. Furthermore, the results in the previous section hold for adversarial models, designed for "worst case" inputs. In practice however, both the job arrivals processes and the rate regions are stochastic. We propose a new model to deal with those two issues that have the following extra assumptions:
Assumption 2.5.1: *1.* We assume a frame structure: At the beginning of a frame of size D, some jobs arrive to the BS to be transmitted to users. By the end of the frame after D slots, all jobs expire, and the system is empty. Note that jobs can still have different deadlines as long as they are all upper bounded by D. The frame structure has been extensively used in modeling deadline-constrained traffic (Bivins, T.H., 2014) [8]. This assumption has been shown to adequately approximate practical scenarios, while enabling the design of efficient scheduling algorithms with deterministic bounds on delay. We assume that there are l-job classes with specified deadlines, reward functions, and sizes. Each of these l-classes arrive at the beginning of the frame according to an i.i.d arrival process A_k. We assume that the number of the new jobs arriving at the beginning of a frame can be deterministically bounded, i.e., $(m(t)) \leq M$, where m(t) is a random variable representing the number of active jobs at time, We assume that the instantaneous rate region **R**[t] is sampled every time slot from a set of finite convex regions in an i.i.d manner unknown to the BS. The realization of rate regions over a frame is denoted as R_k. The new formulation is presented in (2.5.1). Our goal now is to maximize the long-term average expected rewards over frames $k = 1,...,K$. We denote the jobs that arrive at frame k as J^k. In (2.5.1b), we introduce a new constraint to guarantee fairness by ensuring that every user gets an expected **timely-throughput** higher than δ_n. Timely-throughput is the amount of traffic delivered within the deadline over a period of time. It has been used extensively to analyze networks with realtime traffic. The function $U()$ simply maps the job j to its intended user We refer to a random realization of job arrivals and rate regions over a frame as q. The optimization problem (2.5.1) can be solved by a stationary scheduler that maps

$(k+1)D-1$

Source: Author

2. Virtual Queue Structure
To deal with the new timely throughput constraints (2.5.1b) for each user n, we define a virtual queue that records constraint violations. For every frame, the amount of
T unserved work under the δ_n requirement, $\delta_n - {}^X A_{tj} x_{tj}$ is added to the queue, i.e.,
t=1 the queue is updated as follows:

where $(x)^{+} = \max(0,x)$. There are two time-scales at play here. First, the slower frame-level time scale. At the beginning of a frame, jobs arrive and by the end of the frame, those jobs expire. Second, the faster slot level time-scale, where the channels change and the BS allocates rates **x**. Each frame consists of *D* time slots where all jobs are guaranteed to expire by the end of the frame by Assumption 2.5.1. Virtual queues are used to analyze the time-average constraint violation for a given scheduling policy. It can be shown that stability of the virtual queue ensures that the constraint is satisfied in the long term.
Lemma 2.5.1. *For any user n, the virtual queue length upper bounds the constraint violation at all times as follows:*

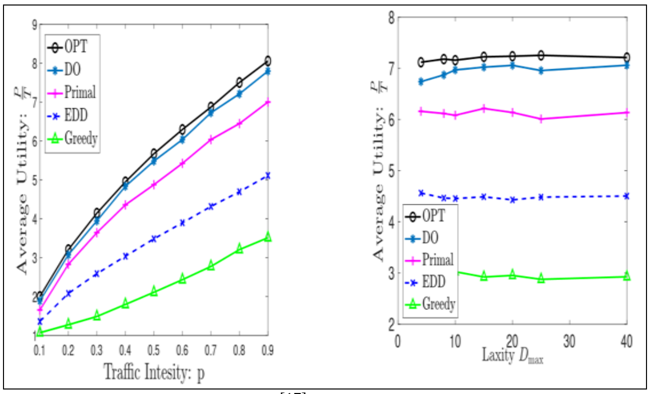
$$\beta tj \geq f\left(\sum_{s=0}^{t} Asjxsj\right) \quad (C\sum_{s=0}^{t} \frac{AsjXsjx^{2}}{Yj} -$$

Source: vbjerg, B. (2006)

Furthermore the mean rate stability defined as:

$$\lim_{K\to\infty} \frac{\mathbb{E}(Q_n[K])}{K} = 0 \quad (2.5.5)$$

D Look-ahead Algorithm
Before explaining our algorithm, we present and analyze a non-causal frame-based algorithm that we refer to as the D look-ahead algorithm. The benefits of this hypothetical algorithm are two-fold: First, it guides our design of the practical LFDO algorithm in the next section, and second, it will be crucial in analyzing the performance of LFDO.
OPT. Interestingly, there is a slight performance degradation for very small values

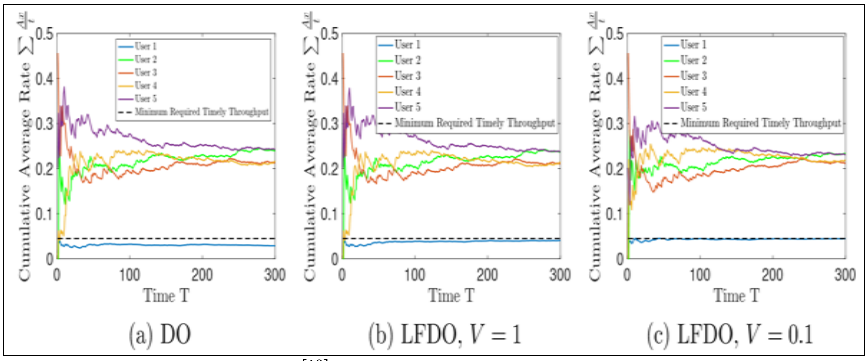


Source: Dodge, P.R. (2011) [17]. Managing School behavior

Fig 10: D Look-ahead Algorithm

(a) Varying *p* (b) Varying D_{max}
Figure 2.2: Comparison of performance of different algorithms
of D_{max} when deadlines are very tight. This is consistent with our findings regarding the dependence of competitive ratio bound on F_{max}, the job-size-to-capacity ratio.
Performance of LFDO**:** In Fig. 2.3, we simulate the system for five users. We set up the simulation, such that User 1 consistently gets low feasible rates compared to other users. In particular, we sample the random rates such that User 1 can get a maximum timely throughput of 0.05, and other users can get up to 0.5 timely throughput. The instantaneous rate region is the convex hull of random rates. We set a minimum timely throughput constraint of 0.045, thus pushing the system to the boundary of the "capacity region" by forcing User 1 to operate very close to its upper limit. In Fig. 2.3a, we show the timely throughput of all users under DO. Since DO tries to maximize reward with no regard to timely throughput constraints, we see that User 1 converges to a timely throughput well below the requirement. In Fig.
2.3b, we run LFDO for the same system with $V = 1$. Despite the improvement over DO, the convergence to the required timely-throughput level is slow since virtual queues are allowed to backlog before being cleared. In Fig. 2.3c, we set $V = 0.1$ emphasizing the importance of timely throughput constraints. The result is that
Figure 11: Resource allocation per user under DO and LFDO
Source: Author, 2024
User 1 can now satisfy the constraint with fairly quick convergence at the expense of slightly decreased reward (within 95% of DO reward). This outlines the previously stated trade-off between the reward and the timely throughput guarantees. We have studied the problem of resource-allocation of low-latency bandwidth-intensive traffic. We have formulated the problem as an online convex optimization problem, developed a low-complexity Primal-Dual DO algorithm and derived its competitive ratio. We have demonstrated that our algorithm is efficient *and does not rely on deadline information*. We have also proposed the LFDO algorithm that modifies DO to satisfy long-term stochastic timely-throughput constraints. We have shown via simulations that our proposed algorithms tracks the offline optimal solution very closely and performs better than existing solutions. In the future work, we aim to understand the properties of DO algorithm better, for example, we aim to analyze how

many jobs are served to their completion. This will enable us to expand the algorithm to serve traffic that must be served to completion as well as traffic that has the partial utility property. We aim to develop our work to take the unreliability of wireless channels and inaccurate channel estimations into account. We also plan to test our algorithm with a real-time setup through the variety of traffic seen in 5G networks.



Source: Biklen, S. K. (2003) [10]. Qualitative research for education

Fig 11: Resource allocation per user under DO and LFDO

5. Overview

This chapter looked at the conclusion and recommendations.

5.1 Conclusion

The culmination of this comprehensive research endeavor on wireless ad hoc networks has yielded a rich tapestry of insights, offering a profound understanding of network performance and user experiences within this dynamic and evolving landscape. Through a meticulous combination of quantitative and qualitative data collection methods, a holistic perspective of wireless ad hoc networks has been unveiled, providing valuable empirical metrics and human-centric narratives that contribute to the foundation of this conclusion. The research findings reveal that wireless ad hoc networks hold immense potential for fostering seamless communication in diverse environments. Participants expressed overall satisfaction with the network's ability to establish ad hoc connections rapidly, adapt to changing conditions, and facilitate peer-to-peer communication. The flexibility and versatility of these networks make them well-suited for scenarios where traditional infrastructure-based communication is limited or impractical.

However, the journey of exploration also unraveled certain challenges that warrant consideration. The study identified occasional packet losses and delays in larger and more complex network configurations, affecting the overall user experience. Additionally, energy efficiency emerged as a significant concern, with some nodes experiencing higher power consumption than others, leading to potential energy imbalances and reduced network lifetime. The study also revealed that user preferences and experiences varied significantly across different user segments and usage scenarios.

5.2 Recommendations

Based on the comprehensive research conducted on wireless ad hoc networks, the following recommendations are proposed to address the challenges identified and optimize network performance, user experiences, and sustainability: Network Optimization: To enhance network stability and reliability, network designers and researchers should focus on optimizing routing mechanisms and employing error correction strategies. Developing robust and efficient routing protocols can minimize packet losses and delays, resulting in improved overall network performance. Energy-Efficient Solutions: Energy-aware routing protocols should be adopted to address energy efficiency concerns. Implementing intelligent power management algorithms that distribute power requirements across nodes can ensure a balanced energy consumption, extending the network's lifetime and reducing the likelihood of energy imbalances. User-Centric Design: Emphasize user-centric design principles in the development of wireless ad hoc networks. Understanding the diverse needs and preferences of different user segments is essential for creating intuitive and tailored solutions. Engaging users in the design process through participatory approaches can result in more user-friendly and satisfying network experiences.

Dynamic Network Adaptation: Design self-adaptive networks capable of dynamically adjusting configurations based on changing conditions. Developing networks that can automatically respond to variations in node availability, traffic load, and environmental factors can enhance network efficiency and adaptability. Longitudinal Studies: Conduct longitudinal studies to track network performance and user experiences over extended periods. Long-term observations can reveal trends, identify evolving challenges, and support the development of sustainable network solutions. interdisciplinary Collaboration: Foster collaboration between researchers, engineers, and network practitioners to bridge the gap between theory and practice. Interdisciplinary efforts can lead to innovative solutions and practical implementations, driving advancements in wireless ad hoc networking. Security Enhancements: Strengthen network security measures to protect against potential threats and vulnerabilities. Implementing robust encryption protocols and authentication mechanisms can safeguard data transmission and ensure network integrity. Scalability Considerations: Evaluate network scalability in diverse scenarios, ranging from small-scale deployments to large-scale networks. Ensuring that the network can accommodate an increasing number of nodes without sacrificing performance is crucial for long-term viability.

6. Acknowledgement
I thank the almighty God, the Creator of heavens and earth. Frankly speaking, He is the one who has been with me from the very beginning of this work, enlivening me and carrying me through all challenges and obstacles. Indeed, He is worthy of all praise and glory!! My sincere thanks and undying gratitude are all extended to my supervisor, who tirelessly have been there for me, supporting me through and through to ensure the survival of my academic dream. Your thoughtfulness and professionalism in revising this work are all hailed as useful tips for making this proposal a success. In you I have found a true academic guidance and mentorship, an incomparable benevolence to be treasured incessantly. My indebtedness also goes to my family, relatives and comrades who determinedly boosted up my academic aspiration. I hope that your benevolent support and silent prayers be awarded abundantly. To all my lecturers, I thank you for your hearty guidance. To me you are cherished heroes without whom this work would be impossible.

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