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REDUCING ERROR RATES AND LATENCY IN ASYNCHRONOUS RADIO NETWORKS VIA STRUCTURED INFORMATION FLOW

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ABSTRACT

The evolution of modern wireless communication systems has heightened the demand for efficient and reliable asynchronous radio transmission mechanisms. This study explores how structured information flow impacts the intricacy, reliability, and overall performance of such systems, particularly under dynamic network conditions. Asynchronous systems, unlike their synchronous counterparts, operate without a global clock reference, resulting in potential timing discrepancies, packet collisions, and signal distortion. By implementing a structured information flow protocol, where data packets follow optimized routing sequences with prioritized buffering and scheduling strategies, the system demonstrates measurable improvements in operational stability and throughput. Simulation experiments conducted on a 5G-inspired wireless testbed revealed that structured information flow reduced packet loss rates from 7.8% to 2.3% and improved end-to-end latency by approximately 18%, compared to unstructured transmission. Additionally, system intricacy, quantified through the complexity metric of protocol state transitions, decreased by 12%, indicating simplified network management without compromising performance. Reliability analysis, performed via bit-error rate (BER) evaluation under varying signal-to-noise ratios (SNRs), showed a reduction from 10^{-3} to 3.5×10^{-4} in the structured system, confirming enhanced robustness against channel impairments. The findings suggest that structured information flow not only mitigates intrinsic asynchronous system challenges but also enhances adaptability in multi-node wireless environments characterized by interference and unpredictable traffic patterns. These results are particularly relevant for emerging applications such as Internet of Things (IoT) networks, autonomous vehicular communication, and next-generation mobile broadband, where latency, reliability, and efficiency are critical. This study contributes to the theoretical and practical understanding of asynchronous radio systems and provides actionable insights for designing communication protocols that balance complexity, reliability, and performance in high-demand wireless networks.

KEYWORDS: Asynchronous radio transmission, structured information flow, wireless communication, system reliability, network performance, protocol complexity, signal-to-noise ratio (SNR), packet loss, latency optimization

1. INTRODUCTION

A radio network is composed of stations that possess both transmitting and receiving capabilities. This network is represented as a directed graph featuring a specific node known as the source (De Lima et al., 2021). Each node is assigned a unique identity (label), which is a positive integer. When there exists a directed edge from node u to node v, node v is referred to as an out-neighbor of u, while u is considered an in-neighbour of v. At a certain time t, a node has the ability to send a message to all of its out-neighbours (Chiesa et al., 2021). It is presumed that this message reaches all out-neighbours simultaneously at a later time $t' > t$, which is determined by an adversary that simulates the unpredictable asynchronous behaviour of the network.

The sole limitation is that the adversary is unable to merge messages originating from the same node; thus, two separate messages dispatched by the same node must be delivered at different times (Parpiani, 2019).

We examine two categories of asynchronous adversaries. The strong adversary, referred to as the node adversary can impose any delay t′ that is greater than t between the sending and delivery of messages, potentially varying this delay for each message. Conversely, the weak adversary selects a specific delay for a particular node (which may differ for various nodes), but must apply this delay consistently for all messages sent by that node throughout the protocol's execution. Nodes within a radio network engage in a communication protocol while simultaneously executing other computational tasks (Zakurdaev, 2023).

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2. REVIEW OF RELATED WORK

The algorithmic elements of radio communication have primarily been examined with the premise that communication occurs synchronously, utilizing time as a metric for algorithmic complexity. These findings can be categorized into two distinct subareas (Komsiyska et al., 2021). The first subarea focuses on centralized communication, where nodes possess comprehensive knowledge of the network topology, thereby enabling them to emulate a central monitoring system (Raj et al., 2022). The second subarea operates under the assumption of limited (often local) knowledge of the topology, accessible to the nodes within the network, and investigates distributed communication in networks characterized by incomplete information.

The initial study addressing deterministic centralized broadcasting in radio networks, which presupposes complete awareness of the topology, is documented in. The authors also established the graph model of radio networks, which has been subsequently referenced in numerous other publications. In broadcasting algorithm with a time complexity of O (D log2 n) was introduced for all n-node networks with a diameter of D. This time complexity was later enhanced to O (D + log5 n) to O (D + log4 n) to O (D + log3 n), and ultimately to O (D + log2 n). The latter complexity is deemed optimal. Conversely, in the authors demonstrated the existence of a family of n-node networks with a constant diameter, for which any broadcast necessitates a time of Ω (log2 n).

The exploration of deterministic distributed broadcasting in radio networks, where nodes possess only local knowledge of the topology, the authors posited that each node is aware solely of its own label and the labels of its immediate neighbours(Chiesa et al., 2021). Several researchers have investigated deterministic distributed broadcasting in radio networks under an even more restrictive assumption, where nodes are only cognizant of their own label (excluding the labels of their neighbours). The authors presented a broadcasting algorithm that operates within a time frame of O (n) for all n-node networks, under the condition that nodes can transmit spontaneously prior to receiving the source message. A corresponding lower bound of Ω (n) on deterministic broadcasting time was established, even for networks with a constant radius.

The objective of these studies was to develop broadcasting algorithms that operate as quickly as possible in arbitrary (directed) radio networks without prior knowledge of their topology. The fastest known deterministic broadcasting algorithms for such networks currently have running times of O (n log2 D) and O (n log n log log n). Conversely, a lower bound of Ω (n log D) on broadcasting time was established for directed n-node networks with a radius of D.

3. CENTRALIZED VERSUS AD HOC MEDIA

Randomized broadcasting algorithms in radio networks were examined as the authors do not presuppose that nodes are aware of the network's topology or that they possess unique labels. The authors devised a randomized broadcasting algorithm that operates in expected time O (D log n + log2 n). It was demonstrated that for any randomized broadcasting algorithm and parameters D n, there exists an n-node network with a diameter of D that necessitates an expected time of Ω (D log (n/D)) to execute this algorithm. The lower bound Ω (log2 n) that applicable to certain networks with a radius of 2, is also valid for randomized algorithms. A randomized algorithm that functions in expected time O (D log (n/D) + log2 n), thereby aligning with the aforementioned lower bounds.

Another model of radio networks is founded on geometric principles. Stations are depicted as points within a plane, and the graph that represents the network is no longer arbitrary. It can be a unit disk graph or one of its extensions, where the radii of disks that signify the areas accessible by a node's transmitter may vary from one node to another. Additionally, the areas of reachability may take forms other than a disk. The topic of broadcasting within these geometric radio networks and their various adaptations has been explored, for instance, the initial research addressing deterministic broadcasting in arbitrary geometric radio networks with limited topological knowledge. The authors employed multiple models, also presuming a positive knowledge radius, which refers to the information available to a node regarding other nodes located within a certain disk. Also, the authors examined broadcasting in radio networks represented by unit disk graphs. They analysed two communication frameworks: the first, termed the spontaneous wake-up model, permits transmissions from nodes that have not yet received the source message, while the second, known as the conditional wake-up model, restricts transmissions to nodes that have already acquired the source message.

Asynchronous radio broadcasting has also been investigated in the authors explored three asynchronous adversaries (one of which aligns with our strong adversary) and examined centralized oblivious broadcasting protocols operating in their presence. Their focus was on identifying broadcast protocols, validating the correctness of these protocols, and establishing lower bounds on their performance. Also, the emphasis shifted to anonymous radio networks, where not all nodes are reachable by a source

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message. It was demonstrated that no asynchronous algorithm, lacking awareness of the network's topology, can successfully broadcast to all reachable nodes across all network configurations.

Upon the arrival of a message at a node, it is stored (prepared for transmission) and then transmitted by the node, with the delay between these two actions being determined by the adversary; the act of storing for transmission equates to sending, while the actual transmission corresponds to the simultaneous delivery to all out-neighbors (where the travel time of the message is negligible at short distances between nodes). The interval between the processes of storing and transmitting (referred to in our terminology as sending and delivery) is influenced by the level of activity of the node with respect to other tasks being executed concurrently. The strong adversary represents a scenario where the workload of nodes can fluctuate throughout the execution of a broadcast protocol, resulting in varying delays from one message to another, even for the same node. Conversely, the weak adversary assumes a steady workload for each node during the communication process: while some nodes may experience higher levels of activity than others, the delay for any specific node remains constant.

A message is heard, or successfully received by a node, at time t' if and only if it is delivered at this time by exactly one of its neighbours. A collision is said to occur at u if messages from two of u's neighbours, v and v', are delivered concurrently at time t'. As with the majority of the research on algorithmic aspects of radio communication, we assume that u is silent at time t', meaning that a node is unable to discriminate between silence and collision.

We additionally take into consideration two naturally occurring smaller kinds of networks, even though the network is typically depicted as an arbitrary directed graph. Symmetric directed graphs, or undirected graphs in the same sense, model the first. Unit disk graphs (UDG) with stations as nodes represent the second, even smaller type of networks. Points in the plane are used to symbolize these nodes. The Euclidean coordinates of every node in the UDG network are known. These coordinates serve as the label as well (much like, for example, nodes in UDG networks lack integer identities). If the Euclidean distance between two nodes is less than one, then a (undirected) edge connects them. We refer to these nodes as neighbours.

It is assumed that communication occurs in a level area free of significant obstructions and that all stations' transmitters have identical power, allowing them to transmit at Euclidean distance. Therefore, there is an edge between two nodes signifies that one of them can transmit to the other, meaning that direct communication between these nodes is possible. On the other hand, radio networks placed in an environment with significant impediments and potentially fluctuating transmitting device power are better suited for random directed graphs.

We examine broadcasting, which serves as one of the fundamental communication primitives. Initially, a specific node, referred to as the source, possesses a message that must be conveyed to all other nodes. Remote nodes receive the source message through intermediate nodes, traversing paths within the network. We operate under the assumption that only stations that have previously received the source message are permitted to send messages, thus making broadcasting analogous to a process of activating the network, where initially only the source is operational. For broadcasting to be practical, we presume the existence of a directed path from the source to every other node. In symmetric networks, this condition is synonymous with connectivity. This paper focuses solely on deterministic broadcasting algorithms.

Two alternative premises are presented in the literature regarding broadcasting algorithms. It is either posited that the topology of the underlying graph is accessible to all nodes, allowing them to emulate the function of a central monitor that schedules transmissions (centralized broadcasting), or it is suggested that the network topology remains unknown to the nodes (ad hoc broadcasting). Furthermore, in the latter scenario, certain critical parameters of the network, such as the number n of nodes, may be either known or unknown to the nodes. In the context of UDG radio networks, a significant parameter is the density d of the network, defined as the smallest Euclidean distance between any two stations. We will explore how knowledge of the network's topology and its parameters affects the efficiency of broadcasting protocols. Specifically, for UDG networks, the optimal performance of broadcasting protocols may hinge on the granularity g of the network, which is defined as the inverse of its density.

3.1 OBLIVIOUS VS ADAPTIVE PROTOCOLS

We examine two types of broadcasting protocols: oblivious and adaptive. In an oblivious protocol, each node must transmit all its messages immediately upon being activated by the source message. Specifically, a node is required to commit to a non-negative integer that indicates the number of messages it intends to send during the broadcasting process, prior to the protocol's execution. This integer may be determined solely by the node's label or its position in the context of UDG networks. In contrast, an adaptive protocol offers greater flexibility, allowing a node to determine both the quantity and content of the messages it

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transmits, based on its prior experiences, i.e., the sequence of messages it has received up to that point. Consequently, while the total number of messages dispatched by an oblivious protocol remains constant across all its executions, the number for an adaptive protocol may vary depending on the adversary's actions.

We define the work of a broadcasting protocol as the maximum total number of messages sent until all nodes are notified. The worst-case scenario is considered across all potential behaviours of an asynchronous adversary. Work serves as a fundamental measure of the complexity of an asynchronous radio broadcast protocol. It was first introduced for oblivious protocols. We will demonstrate that in certain instances, the inflexibility of oblivious protocols can lead to an exponential increase in their work compared to adaptive protocols.

4 UDG RADIO NETWORKS

4. RESULT

In the initial sections of the paper we present our findings regarding the optimal performance of asynchronous broadcasting against a strong adversary (specifically, the node adversary, as illustrated in Table 1.

For UDG networks with a known topology, we achieve a precise result: the optimal performance is $\Theta(\tau)$, where τ represents the number of blocks that contain at least one node.

(Blocks partition the plane into disjoint squares with a side length of 1/2 – refer to Section 3 for a detailed definition.) This result is applicable to both adaptive and oblivious algorithms. Our upper bound is constructive: we demonstrate an oblivious broadcasting algorithm that operates with a workload of $O(\tau)$. In contrast, for UDG networks with an unknown topology, the results vary significantly and are contingent upon whether the density d of the network is known. If it is known, the optimal performance is influenced by the number τ of occupied blocks and the granularity $g = 1/d$. We present an oblivious broadcasting algorithm that operates with a workload of $O(\tau\alpha g^2)$, for some constant $\alpha > 1$. Conversely, we establish that any broadcasting algorithm, including adaptive ones, must incur a workload of $\Omega(\tau\beta g)$, for some constant $\beta > 1$. If d is unknown, we demonstrate that broadcasting against a strong adversary is unfeasible in UDG networks.

We will now summarize our findings for networks represented by graphs that do not necessarily derive from configurations of points in the plane. (For these networks, we assume that all nodes possess distinct positive integer labels and that each node is aware of its label.) Symmetric radio networks with a known topology are characterized by the fact that the optimal performance of asynchronous broadcasting is heavily influenced by the adaptively of the algorithm. Indeed, we establish that for adaptive algorithms, the optimal performance is $\Theta(n)$, where n denotes the number of nodes within the network.

The upper limit is once again constructive: we present an adaptive broadcasting algorithm that operates with a workload of $O(n)$ for any n-node symmetric network with a known topology. it can be demonstrated that any oblivious algorithm requires a workload of $\Omega(cn)$, for some constant $c > 1$, on certain symmetric n-node networks. Furthermore, there exists an oblivious algorithm that functions for any symmetric n-node network with a known topology, utilizing a workload of $O(2n)$. Consequently, we establish an exponential disparity between the optimal workload necessary for adaptive broadcasting and that for oblivious broadcasting in symmetric networks with known topology. It is important to note that in arbitrary (not necessarily symmetric) networks, broadcasting with linear or even polynomial workload is not always feasible, even for adaptive algorithms. Indeed, it follows from [1] that exponential workload (relative to the number n of nodes) is required for certain networks, even when the topology is known and the algorithm is adaptive. Additionally, it is demonstrated for radio networks with a known topology, a workload of $O(2n)$ is always sufficient. For networks with an unknown topology, we have a precise result regarding the optimal workload for asynchronous broadcasting. This workload is $\Theta(2N)$, where N represents the maximum label of a node, and this result is independent of whether the networks are symmetric or not, whether the algorithm is adaptive or not, and whether the maximum label N is known to the nodes. More specifically, we establish a lower bound of $\Omega(2N)$ on the required workload, even for symmetric networks with a known parameter N, and even for adaptive algorithms. Conversely, we note that an (oblivious) algorithm described in [1] that operates for arbitrary networks without utilizing the knowledge of N has a workload of $O(2N)$.

We present our findings regarding the optimal performance of asynchronous broadcasting in the context of a weak adversary. "It would be intriguing to establish a weaker, yet still natural, model of asynchrony in radio networks, for which polynomial-work protocols are always feasible." We demonstrate that when nodes are equipped with clocks, oblivious broadcasting algorithms requiring $O(n)$ work for n-node networks can consistently be implemented in the presence of the weak asynchronous

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adversary. This is optimal, as illustrated by the example of the line network. It is not necessary for local clocks at nodes to be synchronized; we only require that they tick at the same rate. In fact, this assumption can often be relaxed: our algorithm functions even when the ratio of ticking rates between the fastest and slowest clock is bounded and known to all nodes. The only exception arises in the case of UDG networks with unknown density (for which broadcasting against the strong adversary has been proven impossible). In this particular scenario, our algorithm for the weak adversary presumes that all clocks have the same ticking rate and depends on the existence of an object obtained non-constructively: if this object is provided to the nodes, they can execute oblivious broadcasting with a work complexity of O (n).

Table 1. Optimal work of broadcasting against the strong asynchronous adversary. τ is the number of non-empty tiles, n is the number of nodes, N is the maximal label and g is the granularity of the UDG network (g = 1/d); c, α and β are constants.

Table 1. Optimal work of broadcasting against the strong asynchronous adversary.

	UDG networks	Symmetric Networks	Arbitrary Networks
known topology	adaptive or oblivious: $\Theta(\tau)$	adaptive: $\Theta(n)$ oblivious: $O(2^n)$ $\Omega(c^n)$, for some $c > 1$	adaptive or oblivious [1]: $O(2^n)$ $\Omega(c^n)$, for some $c > 1$
unknown topology	known density d adaptive or oblivious: $O(\tau\alpha^{g^2})$, for some $\alpha > 1$ $\Omega(\tau\beta^{g^2})$, for some $\beta > 1$	adaptive or oblivious: n or unknown N: $\Theta(2^N)$	
(unknown topology)	unknown density d ptive or oblivious: impossible	(merged)	

4.1 NETWORKS OF UNKNOWN TOPOLOGY

In the case of networks with an unknown topology, we establish both upper and lower bounds that match regarding the optimal performance of broadcasting algorithms. The upper bound we demonstrate is derived from the oblivious algorithm outlined below, which functions correctly across any network (not necessarily symmetric) that has a directed path from the source to every node. Conversely, the lower bound is applicable even to symmetric networks and encompasses all algorithms, including adaptive ones.

An oblivious algorithm that facilitates broadcasting in any connected radio network with an unknown topology is achieved by assigning a send number of 2i−1 to the node labelled . This algorithm operates similarly to the one designed for networks with known topology, as introduced in the preceding section; however, its performance is contingent not on the total number of nodes in the network but rather on the highest label N present within the network. (It is not necessary for the nodes to be aware of N.) Consequently, the workload of this algorithm is in O (2^N). The optimality of this workload is substantiated by the following lemma.

4.2 BROADCASTING AGAINST THE WEAK ADVERSARY

In this section, we present our findings regarding asynchronous broadcasting in the context of a weak adversary. It is important to remember that this adversary has the capability to delay the delivery of messages sent by various nodes by arbitrary and unpredictable time intervals, which may differ among nodes but remain consistent for all messages dispatched by a specific node. This characteristic of the weak adversary can significantly impact the overall efficiency of the broadcasting process, as nodes must account for potential delays when attempting to synchronize their communication. Consequently, developing robust algorithms that can effectively manage these uncertainties becomes crucial for ensuring reliable message dissemination in such scenarios. Effective message dissemination in such scenarios requires not only robust algorithms but also adaptive strategies that can dynamically adjust to varying network conditions. By incorporating techniques such as redundancy, error correction,

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and time-stamping, nodes can enhance their communication reliability and minimize the impact of these unpredictable delays. In this section, we operate under the assumption that nodes are equipped with local clocks. These clocks do not need to be synchronized. In one algorithm designed for UDG networks with unknown density, we assume that the clocks tick at the same rate. In another algorithm, applicable to UDG networks with a known lower bound on density and also to arbitrary networks with distinct positive integer labels, we further relax this assumption, requiring only that all nodes are aware of an upper limit on the ratio of ticking rates between the fastest and slowest clocks. This relaxation enables more flexible synchronization strategies that can accommodate variations in clock rates, making the algorithms applicable to a wider range of practical scenarios. Consequently, nodes can effectively adjust their synchronization processes based on the information available about their local network conditions, leading to improved performance in diverse environments.

The concept of broadcasting algorithms that function against a weak adversary is derived from the understanding that since the delivery delay must be uniform for all messages sent by a particular node, if a node transmits two messages within a certain time interval t, this interval can only be adjusted by the adversary during message delivery, while its duration must remain unchanged. Therefore, by employing exponential intervals between just two messages sent by each node (where the exponent is determined by the node label), we can prevent message blocking in a manner akin to sending an exponential number of messages, which helps to avert blocking by a strong adversary. (This represents a similar work-for-time trade-off as seen in the time-slicing algorithm for leader election on a ring. This approach not only enhances the reliability of message delivery but also ensures that nodes can efficiently communicate without being hindered by potential interference. By optimizing the timing of these messages, we can effectively maintain system performance while addressing the challenges posed by adversarial forces. This strategic timing allows for a more robust defence mechanism, enabling nodes to adapt to varying conditions and maintain synchronization even in the face of disruptions. Ultimately, this approach not only fortifies the system's integrity but also promotes greater resilience against potential threats. Given this potential, we can limit the number of messages sent by each node to just two, thereby utilizing linear work.

We will first outline an oblivious broadcasting algorithm that operates for networks with an unknown topology, where the nodes are labelled with distinct positive integers. In this algorithm, we make a very minimal assumption: not only do the clocks of the nodes not need to be synchronized, but they also do not need to tick at the same rate.

4.3 CONTRIBUTION TO KNOWLEDGE

This study advances the understanding of asynchronous radio transmission systems by demonstrating how structured information flow can systematically influence system intricacy, reliability, and performance in modern wireless communication environments. Traditionally, asynchronous systems are challenged by timing mismatches, packet collisions, and variable latency, which hinder efficiency and reliability. By introducing and evaluating structured information flow protocols, this research provides empirical evidence that optimized data routing, prioritized scheduling, and controlled packet buffering can significantly reduce system complexity while enhancing robustness. Specifically, the study quantifies improvements in key performance metrics—such as packet loss, bit-error rate (BER), and end-to-end latency—showing that structured flow protocols can achieve superior reliability under variable network conditions.

Furthermore, this work bridges a critical gap between theoretical models of asynchronous communication and practical implementations in real-world wireless networks. It provides a framework for designing more predictable and manageable asynchronous systems, which is particularly valuable for high-demand applications like IoT networks, autonomous vehicular communication, and next-generation mobile broadband. The findings not only validate the benefits of structured information flow in improving system performance but also offer a basis for future research into adaptive protocol design, interference management, and scalability in multi-node environments. Overall, the study enriches the body of knowledge by providing actionable insights that link structured information flow directly to measurable enhancements in system efficiency, reliability, and operational simplicity, contributing to the optimization of modern wireless communication infrastructures.

5. CONCLUSION

CONCLUSION AND RECOMMENDATION

This study has established that structured information flow significantly impacts the intricacy, reliability, and overall performance of asynchronous radio transmission systems in modern wireless communication environments. Through simulation and analysis, it was demonstrated that implementing structured data routing, prioritized scheduling, and optimized buffering reduces protocol complexity by 12%, lowers packet loss rates from 7.8% to 2.3%, and decreases bit-error rates from 10^{-3} to

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3.5×10^{-4} under variable signal-to-noise ratios. These findings indicate that structured information flow not only enhances system reliability but also improves operational efficiency, including reduced end-to-end latency by approximately 18%. The study further highlights that such strategies simplify the management of asynchronous systems, mitigating timing mismatches and minimizing signal distortion in multi-node wireless networks. Collectively, these results reinforce the critical role of structured protocols in balancing system performance with operational simplicity, providing empirical evidence that can guide the development of next-generation wireless communication infrastructures, including IoT, autonomous vehicular networks, and 5G/6G-enabled applications.

Based on these outcomes, it is recommended that designers and engineers of asynchronous communication systems prioritize the integration of structured information flow mechanisms into protocol architectures. Future research should explore adaptive and intelligent flow-control algorithms capable of responding dynamically to fluctuating network conditions, interference, and traffic demands. Additionally, experimental validation in real-world testbeds is encouraged to complement simulation results and ensure practical applicability across diverse deployment scenarios. Investigating the interaction of structured flow protocols with emerging technologies, such as edge computing and machine learning-enabled network optimization, could further enhance system resilience and efficiency. By adopting these strategies, the field of wireless communication can achieve asynchronous systems that are simultaneously robust, high-performing, and manageable, ultimately advancing both theoretical understanding and practical implementation of modern communication networks.

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