

Dynamic State-Aware Channel Selection for IEEE 802.11bn Non-Primary Channel Access

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Abstract—The evolution of wireless local area networks (WLANs) toward the IEEE 802.11bn standard (Wi-Fi 8) indicates a shift from prioritizing peak physical-layer throughput to achieving Ultra-High Reliability (UHR). As Wi-Fi standards expand channel bandwidths, the medium access control (MAC) architecture remains constrained by the primary channel bottleneck. Under the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol, when the primary channel is occupied by an Overlapping Basic Service Set (OBSS), devices enter a deferral state, leading to spectrum underutilization across secondary channels. To address this issue, the IEEE 802.11 UHR task group introduced the Non-Primary Channel Access (NPCA) mechanism. However, the current standard draft restricts each BSS to a static, single Non-Primary Channel (NPCH), making the network vulnerable to secondary channel congestion. This paper investigates the limitations of the single-anchor NPCA protocol and proposes a Dynamic Multi-NPCH Selection architecture to improve overall channel access efficiency. By relaxing the constraint of the NPCA transmission from a fixed secondary anchor, our framework introduces three schemes: Static Single-NPCH Selection (SSNS), Periodic Randomized NPCH Selection (PRNS), and Dynamic State-Aware NPCH Selection (DSANS). The proposed architectures allow the BSS to evaluate spectral conditions and select a suitable available channel, thereby enhancing spectrum utilization and reducing latency in dense deployment scenarios.

Index Terms—IEEE 802.11bn, Wi-Fi 8, Ultra-High Reliability (UHR), WLAN, Non-Primary Channel Access (NPCA), Medium Access Control (MAC), Overlapping BSS (OBSS)

I. INTRODUCTION

The development of the IEEE 802.11 standard has traditionally focused on increasing data rates through physical layer (PHY) innovations and channel bandwidth expansions. However, in dense Overlapping Basic Service Set (OBSS) deployments, intense channel contention often leads to unpredictable access delays and severe latency spikes. Driven by the stringent low-latency and deterministic requirements of emerging applications, such as extended reality (XR), industrial automation, and mission-critical IoT, the IEEE 802.11 task groups have shifted their focus for the forthcoming IEEE 802.11bn (Wi-Fi 8) standard toward ensuring Ultra-High Reliability (UHR) [1]–[4].

A main cause of inefficiency in wideband Wi-Fi operations is the structure of the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol, specifically its reliance on a primary channel. A Basic Service Set (BSS)

uses its primary channel for control frame exchanges and backoff countdowns. In dense OBSS environments, an OBSS transmission on the shared primary channel causes the target BSS to defer its transmission. Because the target BSS's MAC state machine is paused by the primary channel deferral, its wideband transmission cannot proceed, even if the secondary spectrum is idle.

To resolve this issue, the IEEE 802.11 UHR task group proposed the Non-Primary Channel Access (NPCA) mechanism. NPCA allows a Wi-Fi 8 Access Point (AP) and its associated stations (STAs) to move their contention anchor to a designated secondary channel when their default primary channel is occupied by an OBSS. However, the current IEEE 802.11bn draft standard requires a BSS to advertise and utilize only a single, statically defined Non-Primary Channel (NPCH). If this assigned NPCH experiences interference from another OBSS, the NPCA transmission cannot proceed, resulting in unresolved congestion.

To address these limitations, this research proposes a Dynamic Multi-NPCH Selection architecture. Instead of relying on a single predefined channel, the proposed mechanisms enable the BSS to monitor the status of multiple secondary channels and select a more suitable spectrum segment for the NPCA transmission. By introducing and comparing three NPCH selection schemes, this paper provides an architectural framework for enhancing NPCA efficiency and robustness in the IEEE 802.11bn specification.

A. Related Work

Recent studies have begun exploring the potential and limitations of the NPCA mechanism in the upcoming Wi-Fi 8 standard. Bellalta et al. [5] proposed a Continuous-Time Markov Chain (CTMC) model to evaluate the standard NPCA, demonstrating its ability to mitigate the OBSS performance anomaly and improve throughput compared to legacy networks. López-Pérez et al. [6] investigated NPCA's effectiveness in hidden node scenarios, highlighting that synchronization issues and partial visibility can severely degrade performance when the BSS is locked to a specific channel. Furthermore, Wei et al. [7], [8] developed analytical models to comprehensively evaluate the throughput and delay performance of the NPCA protocol, identifying fundamental capacity limits under the standard framework.

While foundational works validate the theoretical benefits of NPCA, they are predominantly predicated on the current standard draft's assumption of a static, single non-primary channel. This single-anchor design leaves the network highly vulnerable to secondary channel congestion and localized interference. Beyond these analytical models, recent research has explored advanced scheduling and learning-based techniques to achieve UHR. For instance, multi-AP joint scheduling provides reliable latency guarantees through coordinated transmission [9], yet it demands strict inter-AP synchronization. Concurrently, AI-driven approaches—such as Multi-Agent Reinforcement Learning (MARL) for contention window optimization [10] and Deep Q-Networks (DQN) for adaptive NPCA decision-making [11]—have demonstrated significant throughput improvements. Despite their effectiveness, these learning-based methods often introduce substantial training overhead and high computational complexity, which can hinder real-time responsiveness in highly dynamic OBSS environments.

To address both the structural limitations of the single-anchor design and the computational burdens of AI-driven methods, this research proposes a Dynamic Multi-NPCH Selection architecture. Instead of relying on a predefined secondary anchor or complex training algorithms, our framework introduces dynamic, state-aware mechanisms (Periodic Randomized NPCH Selection (PRNS) and Dynamic State-Aware NPCH Selection (DSANS)) that evaluate the real-time availability of the entire wideband spectrum. By relaxing the constraint of a fixed anchor and relying directly on real-time CCA states, our approach effectively circumvents bottlenecks, thereby improving overall channel access efficiency with minimal computational latency and no training overhead.

II. SYSTEM MODEL

To evaluate the operational mechanics of the proposed Multi-NPCH Selection architectures, we establish a MAC-layer system model that outlines the network topology and channel contention behaviors.

A. Network Topology and Overlapping Contention Domains

The framework is based on a dense WLAN deployment scenario. The system models a target BSS operating in close physical proximity to multiple independent OBSSs. The available RF spectrum is divided into multiple discrete 20 MHz sub-channels (e.g., Channels 1 to 4). Channel 1 operates as the primary channel for the target BSS, while the remaining channels serve as secondary channels capable of hosting NPCA operations. To determine channel occupancy, devices rely on the Clear Channel Assessment (CCA) mechanism, utilizing both energy detection and packet detection to evaluate the medium. In this highly congested environment, OBSSs independently operate across different sub-channels, creating a multi-dimensional interference topology. Consequently, an OBSS transmission on the primary channel triggers a busy medium state and invokes a Network Allocation Vector (NAV) deferral at the target BSS, pausing its standard operations.

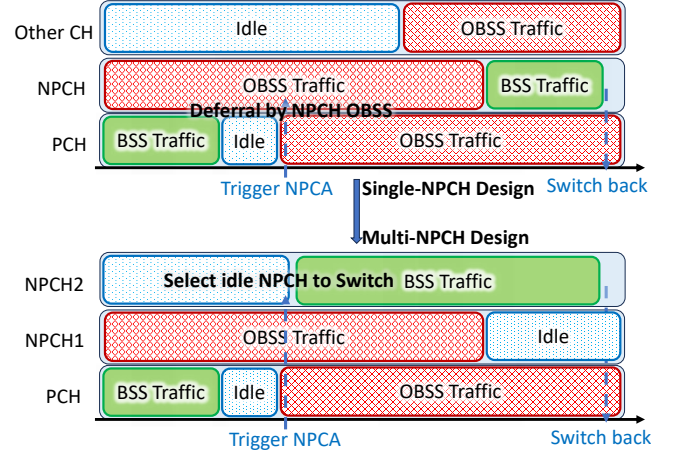


Fig. 1. Timing diagram comparison between the standard Single-NPCH design and the proposed Multi-NPCH design. The static single-anchor approach leads to transmission deferrals when the predefined NPCH is busy, whereas the dynamic multi-NPCH architecture allows the BSS to successfully select and switch to an alternative idle channel.

Simultaneously, independent OBSS traffic on various non-primary channels acts as localized interference, effectively blocking specific secondary channels and limiting the available spectrum pool for NPCA failover.

B. Traffic and Contention Behavior

Traffic generation across active nodes is modeled using a Poisson arrival process under varying load conditions. The contention level is categorized into High, Medium, and Low states, corresponding to the density of active devices and the configured Contention Window (CW) sizes. In a standard legacy configuration, a BSS is strictly dependent on the primary channel being idle to initiate a transmission. With NPCA enabled, the system permits active states across different channels, allowing the target BSS to bypass primary channel blockages by shifting operations to an available secondary channel. However, the efficiency of this mechanism is heavily dictated by the independent occupancy rates of both the primary and non-primary channels. If the pre-assigned NPCH is also congested by independent OBSS traffic, the BSS encounters severe collisions or prolonged deferrals, undermining the intended throughput benefits of the standard NPCA mechanism.

III. PROPOSED METHOD: MULTI-NPCH-BASED NON-PRIMARY CHANNEL ACCESS

The baseline NPCA mechanism is susceptible to secondary channel congestion due to its single-anchor design. To address this, we propose a Multi-NPCH selection architecture that utilizes the available wideband spectrum to improve overall transmission efficiency. We categorize this architecture into three operational schemes.

To intuitively illustrate the structural limitations of the current standard and the advantages of our proposed framework, Fig. 1 presents a timing diagram comparison of channel

access operations. In the Single-NPCH Design, the BSS is statically anchored to a predefined NPCH. When the primary channel (PCH) is occupied by an OBSS, the BSS triggers the NPCA mechanism and switches to the NPCH. However, if the predefined NPCH is also congested, the BSS suffers from a prolonged deferral, wasting other idle secondary channels (e.g., Other CH). Conversely, the proposed Multi-NPCH Design eliminates this bottleneck. Upon detecting an OBSS transmission on the PCH, the BSS evaluates the real-time status of multiple non-primary channels (e.g., NPCH1 and NPCH2). By dynamically selecting an idle channel (NPCH2) to switch to, the BSS successfully avoids the localized interference on NPCH1, ensuring immediate channel access and reliable data transmission.

A. Static Single-NPCH Selection (SSNS)

The Static single-NPCH Selection (SSNS) scheme aligns with the current standard drafts. In this scheme, the target AP assigns one specific secondary channel (e.g., Channel 2) to serve as the sole NPCH. This selection is broadcasted to all associated STAs via beacon frames. When an OBSS occupies the primary channel, the BSS will only attempt to switch to this assigned NPCH. The primary channel of the target BSS is fixed to Channel 1, while its NPCH is initially assigned to a predetermined channel at the beginning of simulation, no further reassignment is performed regardless of the varying channel occupancy condition. While this scheme has low MAC-layer signaling overhead, its structure is fixed. If the selected NPCH has a higher OBSS load, the NPCA transmission efficiency will be lower.

B. Periodic Randomized NPCH Selection (PRNS)

To mitigate the low NPCA efficiency observed in the SSNS scheme, we introduce the Periodic Randomized NPCH Selection (PRNS) architecture. In the PRNS scheme, the primary channel of the target BSS is fixed to Channel 1, while its NPCH of the target BSS is periodically reassigned at predefined time intervals. This assignment is then synchronized with the STAs. By distributing the NPCH selection over time, PRNS averages the collision probability across the wideband spectrum.

C. Dynamic State-Aware NPCH Selection (DSANS)

The Dynamic State-Aware NPCH Selection (DSANS) scheme operates as an adaptive, opportunistic access mechanism. In the DSANS scheme, the target BSS monitors the CCA status and traffic loads of all available secondary channels, and the NPCH of the target BSS is dynamically selected according to the channel occupancy condition. Specifically, the target BSS preferentially assigns its NPCH to the channel with idle among the available non-primary channels. As a result, the target BSS continuously adapts its NPCH selection to mitigate channel contention and improve overall utilization efficiency in multi-OBSS environments. This scheme enhances overall channel access efficiency by dynamically transitioning only to a clear NPCH, thereby avoiding meaningless switching attempts to busy channels.

IV. SIMULATION RESULTS

A. Simulation Settings

The proposed NPCA selection schemes are evaluated using a custom simulation framework developed for multi-channel wireless analysis. The simulation scenario consists of four orthogonal channels and five access points (APs). Among those APs, four APs are configured as overlapping basic service sets (OBSSs), each independently operating on one channel. A target Basic service set (BSS) coexists with the same environment. The primary channel of the target BSS is fixed to Channel 1, whereas different NPCH assignment strategies are adopted according to the proposed methods. The simulator models channel occupancy, channel contention behavior, and NPCH reassignment processes to evaluate total throughput and channel utilization efficiency under different arrival rates. Table I outlines the simulation parameters and channel transmission settings.

TABLE I
SIMULATION PARAMETERS

Parameter	value
Simulation Time(s)	30
Number of Channel	4
Channel Bandwidth (MHz)	20
Packet Size(Bytes)	8184
CW_{min}	15
CW_{max}	1023
Slot Time (μs)	9
SIFS (μs)	16
DIFS (μs)	34

B. Simulation Scenarios

To evaluate coexistence performance under different network load conditions, four traffic scenarios are considered in the simulation. The traffic load of each OBSS is categorized into three levels: High, Medium, and Low, with traffic arrival rates of 0.8, 1/32, and 1/1024, respectively.

The evaluated traffic configurations are summarized in Table II. Note that in our evaluation, certain channels are designated with a Variable (Var) load. Instead of being statically fixed at a Low, Medium, or High level, the OBSS traffic generation rate on these Var channels dynamically scales proportionally with the x-axis values (OBSS arrival rate) in our simulation plots. This specific setup allows us to rigorously observe the system's robustness and the effectiveness of the NPCA mechanism against varying background interference.

- 1) **Low-load OBSS Traffic on Primary Channel:** The scenario represents a mixed traffic environment where the OBSS operating on the primary channel of the target BSS experiences low traffic load, while Channel 2 operates under high traffic conditions and the remaining channels maintain low traffic activity.
- 2) **Medium-load OBSS Traffic on Primary Channel:** The scenario represents a mixed traffic environment in which the OBSS operating on the primary channel of the target BSS experiences a medium traffic load, while Channel 2

operates under high traffic conditions and the remaining channels maintain low traffic activity.

- 3) **High-load OBSS Traffic on Primary Channel:** The scenario represents a high traffic environment in which both Channel 1 and Channel 2 experience a high traffic load, while the remaining channels operate under low traffic conditions.

TABLE II
TRAFFIC CONFIGURATIONS OF EACH SCENARIO

Scenario	Ch 1 (PCH)	Ch 2	Ch 3	Ch 4
Low-load OBSS Traffic	L	H	Var	L
Medium-load OBSS Traffic	M	H	Var	L
High-load OBSS Traffic	H	H	Var	L

Note: L = Low-load, M = Medium-load, H = High-load, Var = Variable-load scaling with the x-axis.

C. Performance Analysis

1) *Impact of NPCH OBSS Traffic Arrival Rate on BSS Throughput:* Fig. 2 illustrates throughput performance of the target BSS under different NPCH selection schemes as a function of the OBSS arrival rate. Five schemes are compared, including SSNS with NPCH on Low-load, High-load, and Variable-load, PRNS, and the proposed DSANS scheme. Specifically, for the SSNS under the variable-load condition, the OBSS traffic on the designated NPCH is not statically fixed at a Low, Medium, or High level; rather, it scales up proportionally to the OBSS arrival rate depicted on the x-axis. It can be observed that DSANS consistently achieves the highest throughput under all traffic conditions. This is because DSANS scheme dynamically selects an idle channel as NPCH, thus reducing channel contention between the target BSS and neighboring OBSS. In contrast, SSNS with NPCH on the high-load channel exhibits the worst throughput performance, since the target BSS continuously operates under severe channel contention in high-load traffic conditions. Similarly, the throughput of the variable-load SSNS scheme drops sharply as background traffic intensifies, highlighting the vulnerability of being locked to a static anchor. Meanwhile, PRNS uniformly utilizes the available NPCHs through periodic random reassignment, resulting in higher throughput compared to SSNS. However, its throughput gradually decreases as the OBSS arrival rate increases as a result of increasing channel contention among neighboring OBSS.

2) *NPCH Ineffective Airtime Ratio under Different BSS Arrival Rates:* Fig. 3 illustrates the NPCH ineffective airtime ratio as a function of the BSS arrival rate. In this simulation, five schemes are compared, including a baseline scheme without NPCA, SSNS with NPCH on the low-load channel, SSNS with NPCH on the high-load channel, PRNS, and DSANS. During simulation, SSNS with NPCH fixed on the high-Load channel exhibits a higher NPCH ineffective airtime ratio, even exceeding that of the scheme without NPCA. This is because of the failure to make good use of idle channels and severe channel contention, which reduce the opportunities for transmissions on NPCH.

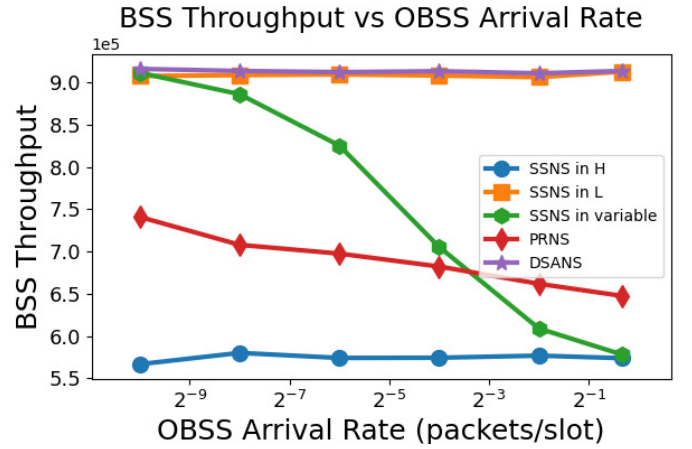


Fig. 2. BSS throughput vs. OBSS arrival rate (packets/slot) under different NPCH selection schemes. Scenario: one high-load OBSS on the primary channel, one high-load OBSS on an NPCH, and two light-load OBSSs on the remaining NPCHs. The arrival rate of one selected light-load OBSS is increased from 1/1024 to 0.8 packets/slot.

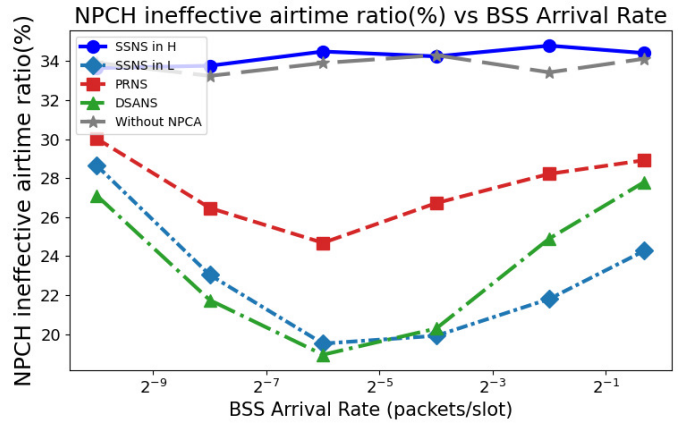


Fig. 3. NPCH ineffective airtime ratio vs. BSS arrival rate (packets/slot) under different NPCH selection schemes. Scenario: Medium-load OBSS Traffic on Primary Channel. This scenario is shown because it most clearly highlights the performance difference among the compared schemes.

As shown in Fig. 3, DSANS and SSNS with NPCH on the low-load channel exhibit low NPCH inefficient airtime ratio, indicating efficient utilization of NPCH sources. As the BSS arrival rate increases, a larger proportion of the target BSS traffic is transmitted on the primary channel. Consequently, fewer transmissions are offloaded to NPCHs, leading to an increase NPCH ineffective airtime ratio. Since DSANS increasingly exploits the primary channel for transmissions, its NPCH ineffective airtime ratio becomes slightly higher than that of SSNS with NPCH on low-load channel.

3) *Impact of Primary Channel (PCH) OBSS Traffic Arrival Rate on NPCH/PCH Throughput Ratio:* Figs. 4–6 illustrate the Data rate ratio between NPCH and PCH under three simulation scenarios, including Low-load, Medium-load, and high-load OBSS traffic conditions on the primary channel, respectively. In each scenario, four schemes are compared: SSNS with NPCH fixed on the Low-load channel, SSNS with NPCH fixed

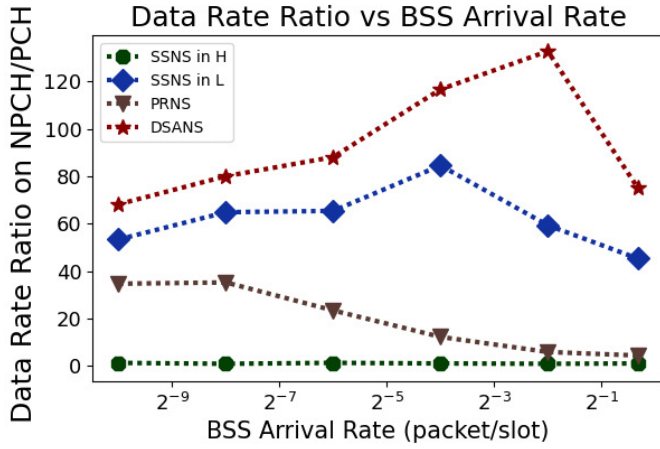


Fig. 4. Data Rate Ratio on NPCH/PCH vs. BSS arrival rate (packets/slot) under different NPCH selection schemes. Scenario: High-load OBSS Traffic on Primary Channel.

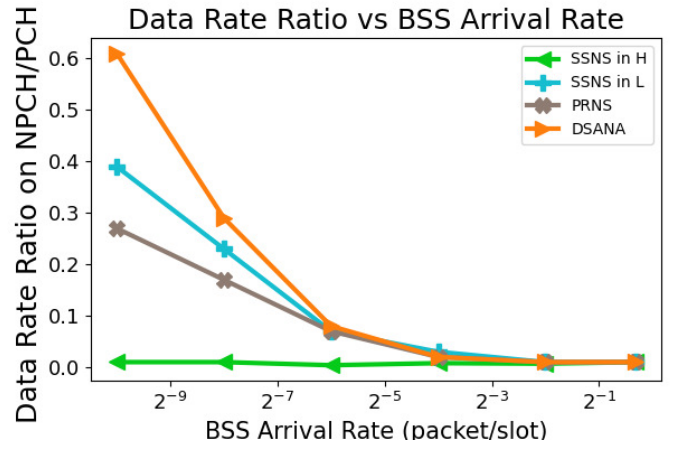


Fig. 5. Data Rate Ratio on NPCH/PCH vs. BSS arrival rate (packets/slot) under different NPCH selection schemes. Scenario: Low-load OBSS Traffic on Primary Channel.

on the High-load channel, PRNS, and DSANS.

Across all scenarios, the NPCH/PCH throughput ratio decreases as the BSS arrival rate increases. This trend can be attributed to the increasing utilization of the primary channel, which reduces the proportion of traffic transmission through NPCHs. In the low-load scenario Fig. 5, the primary channel experiences relatively low contention, providing sufficient transmission opportunities for target BSS. Consequently, the ratio remains lower than in the other scenarios, as the target BSS has less incentive to offload traffic on NPCHs. In the medium load Fig. 6, contention on the primary channel increases, which encourages greater utilization of NPCH resources. As a result, all schemes exhibit a higher ratio compared to the low-load scenario. In the high-load scenario Fig. 4, severe contention on the primary channel further motivates traffic offloading to NPCHs. Therefore, the ratio reaches its highest level among the three scenarios.

Among all schemes, DSANS maintains the highest data rate ratio under almost all traffic conditions, particularly under high-load OBSS traffic conditions. The results demonstrate that dynamic NPCH selection can enable the target BSS to utilize NPCH resources more effectively and distribute traffic more evenly across available channels.

V. CONCLUSION

This paper proposed the Dynamic State-Aware NPCH Selection (DSANS) scheme for Wi-Fi 8 multi-OBSS environments. By dynamically selecting the NPCH according to real-time channel occupancy conditions, DSANS effectively mitigates channel contention among neighboring OBSSs. The simulation results demonstrate that DSANS achieves superior throughput performance and enhanced idle NPCH reuse capabilities compared to the static SSNS and PRNS architectures under various traffic conditions. Ultimately, these results confirm that state-aware, dynamic NPCH selection significantly improves channel utilization efficiency and reliability in dense Wi-Fi 8 networks.

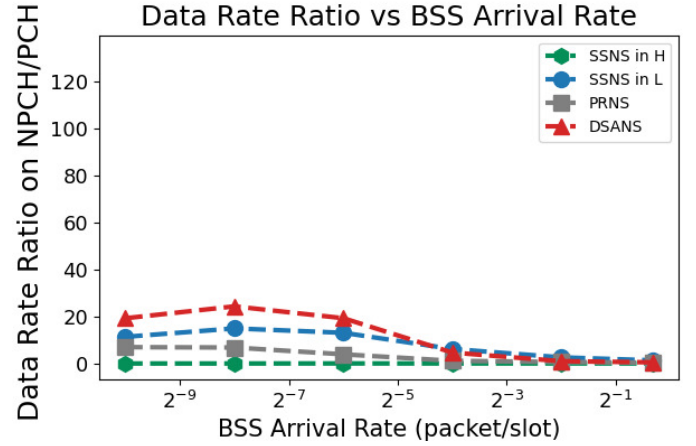


Fig. 6. Data Rate Ratio on NPCH/PCH vs. BSS arrival rate (packets/slot) under different NPCH selection schemes. Scenario: Medium-load OBSS Traffic on Primary Channel.

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