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Overcoming the Challenge of Non-Optimal AP Selection in Wi-Fi Roaming

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***Abstract*—This paper addresses the critical issue of non-optimal Access Point (AP) selection in wireless networks, which significantly impacts network efficiency and user satisfaction. In dynamic wireless environments, particularly those integrating Internet of Things (IoT) applications, clients often face challenges in maintaining optimal connectivity due to suboptimal AP selection and inefficient roaming. This results in degraded network performance, characterized by reduced data transfer speeds, increased latency, and higher likelihood of connection drops. The paper delves into the intricacies of client-AP connectivity, exploring the reasons behind non-optimal AP selection and the lack of efficient roaming. It employs simulation tools and analytical methodologies to offer insights into identifying, analyzing, and resolving these issues. The goal is to enhance the client-AP connectivity experience in wireless networks, ensuring that they are robust, capable, and intelligently adaptive to the dynamic movements and requirements of users. Key strategies discussed include advanced algorithms for AP selection that go beyond mere signal strength, implementation of fast roaming technologies like IEEE 802.11r, 802.11k, and 802.11v, and smart AP management techniques such as load balancing and dynamic channel assignment. The paper also highlights the significant improvements brought by Wi-Fi 6 (802.11ax) in enhancing the Wi-Fi roaming experience through features such as Orthogonal Frequency Division Multiple Access (OFDMA), Target Wake Time (TWT), and BSS Coloring. The paper underscores the need for a comprehensive approach to address the challenge of non-optimal AP selection and efficient roaming in wireless networks. By leveraging advanced selection algorithms, implementing smart AP management strategies, and adopting fast roaming technologies, it is possible to significantly enhance the performance and user experience of wireless networks in our increasingly connected world.**

Keywords-OFDMA (Orthogonal Frequency Division Multiple Access), TWT (Target Wake Time), BSS Coloring, Beamforming, MU-MIMO (Multi-User, Multiple Input, Multiple Output), AP (Access Point), IoT (Internet of Things), STA (station)

I. INTRODUCTION

In the rapidly evolving landscape of wireless communications, the efficiency and reliability of client-Access Point (AP) connectivity remain pivotal for ensuring optimal network performance and user experience. As wireless networks burgeon in complexity and capacity, particularly in the context of Internet of Things (IoT) integration and the expanding reach of Wi-Fi in both public and private spaces, the challenges associated with client-AP connectivity have become more pronounced. Among the most significant of these challenges is the issue of non-optimal AP selection by roaming clients, a problem that has implications for both network efficiency and user satisfaction.

Traditionally, wireless devices, or 'clients', are expected to connect to the closest available AP, ensuring the strongest possible signal strength and, consequently, the most stable and efficient network connection. However, in practice, this ideal scenario is often compromised. A common issue observed in various wireless network environments is that clients do not always connect to the nearest AP. Instead, they tend to maintain a connection with an AP that, although initially the closest at the time of connection, may no longer be the optimal choice as the client moves within the network space. This suboptimal AP selection can lead to several issues, including reduced data transfer speeds, increased latency, and a higher likelihood of connection drops, significantly degrading the overall network performance and user experience.

Moreover, the problem is compounded by the clients' reluctance or inability to switch, or 'roam', to a more optimal AP as they move around. In an ideal wireless network, clients would seamlessly switch to the nearest AP as they move, always maintaining the strongest possible connection. However, due to various factors such as signal strength thresholds set for roaming, client device behavior, and AP load-balancing strategies, this seamless transition is not always achieved. Consequently, clients often remain connected to an AP that is no longer the best option, leading to a network that is inefficiently utilized and a wireless experience that falls short of expectations.

This paper aims to delve into the intricacies of this challenge, analyzing the reasons behind non-optimal AP selection and the lack of efficient roaming in wireless networks. By employing simulation tools and analytical methodologies, this study seeks to offer insights into how these issues can be identified, analyzed, and resolved. The goal is to optimize client-AP connectivity, ensuring that wireless networks are not only robust and capable but also intelligently adaptive to the dynamic movements and requirements of their users.

II. BACKGROUND AND CONCEPTS

Wireless roaming has become a pivotal aspect of modern wireless networks, characterized by the seamless transition of mobile devices between different Access Points (APs) without losing connectivity. This feature is essential in maintaining uninterrupted service as a device moves through different coverage areas. The focus on wireless roaming underscores the critical need for networks to provide consistent, reliable connections across various physical spaces, a challenge amplified by the diverse range of devices and applications relying on these networks.

A. Evolution and Current Demands in Wireless Networks

The evolution of wireless networks has been profoundly shaped by the increasing need for efficient wireless roaming capabilities. Originally, networks based on protocols like 802.11a/b/g were designed for static connectivity. However, the advent of Wi-Fi 6 and similar advanced standards marks a shift towards supporting high-mobility wireless environments. This transition is driven by the growing prevalence of mobile devices and IoT applications, which necessitate seamless roaming across different network coverage areas. Today's wireless networks are tasked with ensuring not only high-speed data transfer but also uninterrupted connectivity as devices move between multiple APs. This evolution reflects the dynamic nature of user environments, ranging from bustling office spaces to expansive smart homes, where consistent client-AP connectivity is vital for both performance and user experience. The capacity of a network to facilitate effective roaming is integral to its design, necessitating sophisticated mechanisms that manage the handover of devices between APs without compromising connection quality or data security.

B. Client-AP Connectivity

The connection between a client device and an AP is a multi-step process that forms the backbone of wireless networking. Initially, a client device scans the environment to identify available networks. Once a network is selected, the device authenticates with the chosen AP, a process that ensures network security and integrity. Following successful authentication, the client obtains an IP address, enabling it to communicate within the network and access broader Internet services. This connectivity, however, is not static. It must be actively maintained, adapting to changing signal strengths, interference, network congestion, and the evolving physical environment. The quality and stability of this connection are paramount, impacting not just data transfer rates but also the overall user experience in terms of reliability and efficiency. [1, 16]

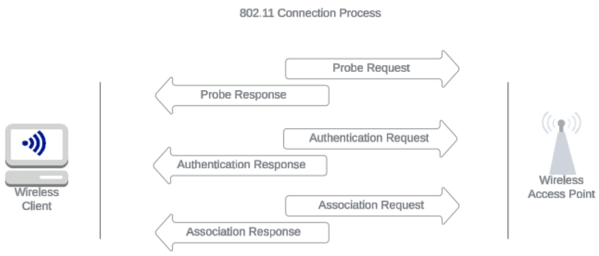

Figure1: Client AP Connectivity [1]

1. Beacons: Access points (APs) periodically broadcast beacon frames to signal their presence and share essential information needed for stations to connect to the network.

2. Probe Request: Stations send out probe requests to identify nearby 802.11 networks, indicating their supported data rates and capabilities, like 802.11n.

3. Probe Response: Upon receiving a probe request, an AP checks for a common data rate with the station. If compatible, it sends back a probe response, detailing its SSID, supported data rates, encryption types, and other capabilities.

4. Authentication Request: The station selects an AP based on the probe responses, ensuring compatibility in terms of SSID, network, and encryption type. It then initiates a low-level 802.11 authentication process with the chosen AP.

5. Authentication Response: The AP responds to the authentication request. If it receives an incompatible frame from an unauthenticated station, it sends a de-authentication frame, requiring the station to restart the authentication process.

6. Association Request: Once authenticated, the station sends an association request to the AP, specifying its chosen encryption types and compatible capabilities.

7. Association Response: The AP, upon verifying that the station's request matches its capabilities, assigns an Association ID to the station and sends back a success message, granting network access.

8. Data Transfer: With the station now successfully associated with the AP, a stable connection is established, allowing for data transfer.

C. Roaming in Wireless Networks

Roaming occurs when a wireless client moves across different coverage areas, necessitating a change in the connected AP to maintain network connectivity. Effective roaming is crucial in environments where mobility is common, such as in office buildings, campuses, and public spaces. The roaming process involves the client assessing the signal quality of its current connection and nearby APs and deciding whether to switch to a different AP for a better connection. [2]

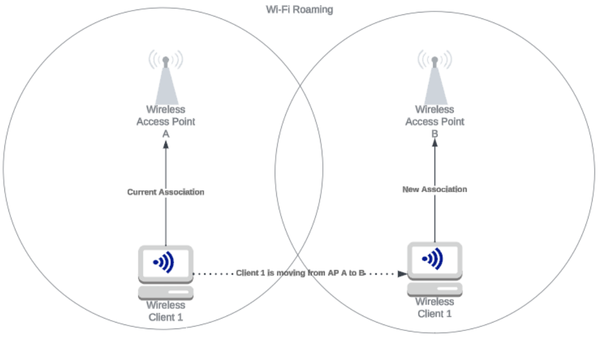

Figure2: Wi-Fi Roaming [10]

Wi-Fi roaming involves several key phases:

- Triggering: Roaming is initiated by a Station (STA) when it detects that the downlink Received Signal Strength Indicator (RSSI) falls below a certain threshold, indicating a need to find a stronger signal.

- Scanning: The STA scans for available Access Points (APs) using either active or passive methods:

- Active Scanning: The STA sends out Probe Request frames and waits for APs to reply with Probe Response frames, helping it identify available APs.
- Passive Scanning: The STA listens for Beacon frames that APs periodically broadcast.
- The choice between active and passive scanning typically depends on the STA's capabilities and the specific requirements of the device (e.g., mobile phones and laptops may support both, while VoIP STAs often prefer passive scanning).

- Selecting: Based on the information gathered during scanning, the STA selects an AP as the target for roaming.

- Handover: The STA chooses a roaming mode compatible with both its own capabilities and those of the network, completing the transition to the new AP.

III. CHALLENGES AND IMPLICATIONS

A. Challenge of Non-Optimal AP Selection

This challenge focuses on the initial decision a client device makes when connecting to an AP. When a device first attempts to connect to a wireless network, it has to choose which AP to connect to. Ideally, this choice should be the closest AP or the one that can offer the strongest signal and best performance. However, this is not always the case due to various factors like signal strength, interference, or even the client device's internal algorithm for AP selection. The key points here are:

- Initial Connection Decision: The focus is on the device's choice of AP at the time of first connecting to the network.
- Sticky Client Issue: A common problem where devices remain connected to an AP that may no longer be the best option, often because they initially connected to that AP and haven't switched despite moving closer to another AP.

B. Challenge of Client Roaming

challenge of client roaming pertains to the device's behavior after it has connected to an AP, specifically how it handles movement within the network's coverage area. When a client moves around, ideally, it should seamlessly switch ("roam") to another AP that offers better connectivity. This challenge is about the device's ability to dynamically and efficiently switch APs as it moves, to maintain optimal connectivity. The key aspects are:

- Client Device Behavior: Different client devices have varying algorithms and thresholds for deciding when to switch to a new AP. These differences can lead to inconsistent roaming behavior.

- AP Load and Signal Thresholds: The decision to switch to a different AP is often based on signal strength thresholds. If these thresholds are not optimally configured, clients might stick to a less ideal AP longer than necessary.

- Environmental Factors: Physical obstacles, interference from other devices, and the architectural layout of a space can all impact signal strength and the efficiency of roaming.

This can impact the overall network in several ways.

- Reduced Data Transfer Speeds: A client connected to a distant AP experiences weaker signal strength, which directly impacts the data transfer speeds. This reduction in speed can be detrimental, especially in environments where high data throughput is essential.

- Increased Network Latency: The distance from the AP and potential obstructions lead to increased latency, which is particularly problematic for applications requiring real-time data transmission, such as VoIP or online gaming.

- Network Congestion and Load Imbalance: Non-optimal AP selection can lead to certain APs being overburdened while others are underutilized. This imbalance creates network congestion, affecting the overall network performance.

In addressing the challenge of non-optimal AP selection and enhancing roaming in wireless networks, several methods and technologies play a crucial role. This section delves into these methods, explaining how they contribute to optimizing client-AP connectivity.

C. Understanding AP Selection Mechanisms

The first step in optimizing client-AP connectivity is understanding the underlying mechanisms that govern AP selection. Typically, wireless clients select an AP based on signal strength (RSSI - Received Signal Strength Indicator). However, this approach doesn't always result in the most efficient connection, especially in dynamic environments. RSSI is measured in decibels from 0 (strongest signal) to -100 (weakest signal) and represents the power level that a wireless device is receiving from the AP. In RSSI-based AP selection, client devices scan for available APs and typically connect to the one with the highest RSSI value.

RSSI	Signal Strength
>-70 dBm	Excellent
-70 dBm to -85 dBm	Good
-86 dBm to -100 dBm	Fair
<-100 dBm to -110 dBm	Poor
<-110 dBm	No Signal

Table1: RSSI Signal Strengths [7]

While RSSI-based selection is straightforward, it has limitations:

- Signal Strength vs. Quality: A strong signal (high RSSI) does not always equate to a high-quality connection. Factors like interference and network congestion are not accounted for in RSSI.

- Dynamic Environments: In environments where clients are moving, RSSI values can fluctuate, leading to potential connection instability.

- Physical Barriers: Walls and other physical structures can affect signal strength, but RSSI does not reflect the quality degradation due to such barriers.

IV. METHODS AND TECHNOLOGIES THAT ENHANCE ROAMING CAPABILITIES

Roaming is the process by which a wireless client moves from one AP to another seamlessly. Optimizing this process is crucial for maintaining a stable and efficient network connection.

A. Client Steering

Client steering in wireless networks involves guiding WLAN clients to the most suitable Access Point (AP) using centrally defined criteria in the Wireless LAN Controller (WLC). This process is particularly effective in networks where APs are centrally managed by a WLC. [3]

- Data Collection: The WLC gathers data on WLAN clients from all connected APs. This data forms the foundation for steering decisions.

- Centralized Configuration: All APs in the network are set up to defer client steering decisions to the WLC.

- Client Connection Process: When an unassociated WLAN client sends a probe request, the APs relay this request and the client's signal strength to the WLC using the Control And Provisioning of Wireless Access Points (CAPWAP) protocol.

- Decision Making: The WLC calculates a value for each AP within the client's range based on three factors: signal strength, the number of clients currently associated with the AP, and the frequency band. These factors are weighted and combined to determine the best AP for the client.

- AP Selection: APs that achieve the highest calculated value, or those within a certain tolerance level, are instructed by the WLC to accept the client upon its next login attempt. Meanwhile, clients attempting to connect prematurely, before the WLC's response, are rejected.

- Handling 'Sticky' Clients: If a client is 'sticky'—not switching to a better AP despite a weaker current connection—the WLC can prompt the currently connected AP to log off the client. This forces the client to connect to the AP offering a stronger connection.

B. Band Steering:

In networks with dual-band APs (2.4 GHz and 5 GHz), band steering technology encourages devices to connect to the less crowded 5 GHz band, which typically offers better performance. [4, 13]

Figure3: Band Steering [8]

As clients move around in a Wi-Fi network, band steering assists in maintaining a stable connection by dynamically determining the best band for each device based on signal strength, device capability, and current network load. This results in fewer disconnects and reconnections, offering a more seamless roaming experience.

C. Implementing Smart AP Management

Smart AP management involves using software tools and algorithms to dynamically manage the APs in a network. They provide significant benefits to the wireless network and improve the roaming experience of clients.[6, 10]

1) Load Balancing

Load balancing ensures that client devices are evenly distributed across all available APs in the network. This prevents any single AP from becoming overwhelmed with too many connections, which can lead to congestion and degraded performance.

2) Dynamic Channel Assignment

Dynamic channel assignment continually assesses the wireless environment to assign the most optimal channel to each AP. This reduces interference from other APs and external sources, which is especially important in dense Wi-Fi environments like office buildings or urban areas.

3) Optimized Bandwidth Usage

By adjusting channels based on current network conditions, dynamic channel assignment ensures that each AP operates on the least congested channel available. This optimizes bandwidth usage, allowing for higher data throughput and better overall network performance.

4) Adapting to Environmental Changes

Wireless environments are dynamic, with interference patterns changing throughout the day. Dynamic channel assignment adapts to these changes, continuously selecting the best channels for APs and thereby maintaining optimal network conditions for roaming clients.

D. Implementing Fast Roaming Technologies

Fast roaming technologies in Wi-Fi are designed to provide a seamless and efficient transition for users as they move from the coverage area of one Access Point (AP) to another, particularly in environments where mobility is common, such as in large office spaces, campuses, or hospitals. The goal of these technologies is to minimize the time and disruption typically experienced during the roaming process, thereby enhancing the overall user experience. Key fast roaming technologies include: [14]

1) IEEE 802.11r (Fast BSS Transition):

802.11r, also known as Fast Basic Service Set Transition, speeds up the authentication process during roaming. It allows the client device to establish a security association with the new AP before it actually roams to that AP. This pre-authentication reduces the time taken to connect to the new AP. By reducing the authentication time, 802.11r minimizes connection delays, which is particularly beneficial for applications that require constant connectivity, such as VoIP and streaming media.

2) IEEE 802.11k (Radio Resource Measurement):

802.11k helps client devices to better understand their Wi-Fi environment to make more informed decisions about roaming. It provides information about the neighboring APs, including their signal strength and available resources. This information allows clients to quickly and efficiently decide when and where to roam. Clients can preemptively identify the best target AP for roaming, thus improving the speed and efficiency of the roaming process.

3) IEEE 802.11v (Wireless Network Management):

802.11v standard allows network administrators to influence client roaming behavior to optimize network usage. This standard enables the network to provide clients with suggestions about potential target APs, balancing the load across the network and ensuring optimal AP selection. By guiding clients to less congested APs, 802.11v can enhance overall network performance and user experience, particularly in high-density environments.

E. Wi-Fi 6 (802.11ax) and Its Impact on Wi-Fi Roaming

Wi-Fi 6 comes with series of advanced features and improvements that enhance overall wi-fi performance. Below sections focus on roaming aspects of it. [11]

1) Orthogonal Frequency Division Multiple Access (OFDMA)

Increased Efficiency with OFDMA: One of the key features of Wi-Fi 6 is Orthogonal Frequency Division Multiple Access (OFDMA). Unlike its predecessor, OFDMA allows multiple users with varying bandwidth needs to be served simultaneously. This efficiency is crucial for roaming, as it ensures that clients can seamlessly switch between APs without experiencing significant delays, especially in dense environments with many users.

2) Target Wake Time (TWT):

Target Wake Time (TWT): Wi-Fi 6 introduces TWT, which allows devices to determine when to wake up and communicate with the AP. This feature not only conserves power but also reduces the contention and overlap in communication, leading to smoother roaming experiences as devices move across APs.

3) BSS Coloring

BSS Coloring: BSS (Basic Service Set) Coloring is a feature in Wi-Fi 6 that helps in mitigating interference from neighboring networks. By "coloring" frames from different APs, devices can differentiate between overlapping networks, reducing the likelihood of interference and ensuring more stable connections during roaming.

4) Other Improments in Wifi 6 that enhance roaming

Higher Data Rates and Improved Performance in Dense Environments is one of the significant improvements. Wi-Fi 6 operates both in the 2.4 GHz and 5 GHz bands and offers significantly higher data rates. This improvement is beneficial for roaming, as it allows for quicker data transfers, reducing the time a roaming device spends at lower speeds during transitions between Aps. Wi-Fi 6 includes technologies like Beamforming and Multi-User, Multiple Input, Multiple Output (MU-MIMO), which enhance signal reliability and range. Better signal strength and reliability facilitate smoother roaming, with fewer drops and stronger connections as users move around. [5, 15]

V. CONCLUSION

This study has comprehensively explored the multifaceted challenge of non-optimal Access Point (AP) selection in Wi-Fi networks, particularly in the context of client roaming. The investigation revealed that traditional methods of AP selection, primarily based on signal strength (RSSI), often fall short in dynamic environments, leading to degraded network performance, increased latency, and a higher probability of connection drops. These issues are particularly pronounced in environments with high user mobility and diverse device ecosystems, such as IoT applications.

The paper highlighted the limitations of RSSI-based AP selection and underscored the necessity for more sophisticated approaches that consider additional factors like network congestion, client device behavior, and environmental influences. To address these challenges, the study examined various methods and technologies that enhance roaming capabilities, such as client steering, band steering, smart AP management (including load balancing and dynamic channel assignment), and the implementation of fast roaming technologies like IEEE 802.11r, 802.11k, and 802.11v.

Moreover, the introduction and impact of Wi-Fi 6 (802.11ax) on the Wi-Fi roaming experience were thoroughly analyzed. Wi-Fi 6, with its advanced features like Orthogonal Frequency Division Multiple Access (OFDMA), Target Wake Time (TWT), and BSS Coloring, offers significant improvements in efficiency, network capacity, and roaming performance. These advancements are crucial for accommodating the evolving demands of modern wireless networks and ensuring a seamless, efficient roaming experience.

In conclusion, the paper asserts that overcoming the challenge of non-optimal AP selection in Wi-Fi roaming requires a holistic approach. This involves leveraging advanced algorithms for intelligent AP selection, implementing smart AP management strategies, and adopting the latest fast roaming technologies. Such measures are vital for enhancing the performance, efficiency, and overall user experience of wireless networks in today's increasingly connected world. As wireless technology continues to evolve, so must the strategies for optimizing client-AP connectivity to meet the demands of diverse and dynamic network environments.

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