Postprint: Interference Mitigation Strategies for High-Density Wi-Fi Deployment Environments

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Abstract

High-density Wi-Fi deployment environments such as banks, office buildings, and shopping malls universally suffer from co-channel interference, which constitutes a critical pain point constraining improvements in user experience and network quality. First, to address this problem, we investigate interference detection techniques and propose an interference degree assessment model for the identification and measurement of Wi-Fi node interference. Subsequently, we introduce a "tolerance + avoidance"anti-interference strategy. The tolerance strategy, grounded in capture effect theory and wireless resource management techniques, enhances data communication quality under interference conditions; the avoidance strategy utilizes a localized channel self-coordination algorithm and a decentralized distributed architecture to resolve collision issues in co-channel interference scenarios. Finally, we implement the anti-interference mechanism WifiAAS. Experimental results demonstrate that this mechanism can improve device performance by 10% without incurring excessive overhead.

Full Text

Preamble

Anti-Interference Strategies for High-Density Wi-Fi Deployment Environments

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Abstract: In high-density Wi-Fi deployment environments such as banks, office buildings, and shopping malls, the pervasive problem of homogeneous interference represents a critical bottleneck constraining user experience and network quality improvements. This paper first investigates interference detection techniques and proposes an interference degree evaluation model for identifying and measuring Wi-Fi node interference. Subsequently, a "tolerance + avoidance" anti-interference strategy is introduced. The tolerance strategy, grounded in capture effect theory and wireless resource management techniques, enhances data communication quality under interference conditions. The avoidance strategy employs a localized channel self-coordination algorithm within a decentralized distributed architecture to resolve conflicts in homogeneous interference scenarios. Finally, the anti-interference mechanism WifiAAS is implemented. Test results demonstrate that this mechanism can improve device performance by 10% without introducing excessive overhead.

Keywords: WLAN; anti-jamming; channel allocation; interference assessment model; distributed architecture

0 Introduction

Wireless local area networks represent a crucial means for public venue users to access network services, with Wi-Fi network services considered standard 配套设施 in high-traffic locations such as hotels, shopping centers, and entertainment venues. As public Wi-Fi service coverage continues to expand, enhancing the anti-interference capability of wireless LAN Wi-Fi devices has become a significant research priority, particularly in high-density deployment environments where homogeneous interference problems are especially pronounced. Two common deployment scenarios exist in public spaces: (a) venues primarily consisting of small 10-15 square meter compartments, such as hotels, KTVs, and restaurants, where operators typically install a Wi-Fi node in each room to ensure normal Internet access for all users; and (b) large spaces of 400 m^2 or more, such as halls, theaters, and sports venues, where operators similarly deploy numerous Wi-Fi devices to meet high-density connectivity demands. Consequently, public wireless LAN construction schemes generally feature large network scale, high node density, and heavy localized load characteristics.

In high-density Wi-Fi deployment environments, homogeneous interference severely impacts the network service quality provided by wireless LANs, degrading user Internet experience and effectively increasing maintenance costs. Current domestic scholars have conducted extensive research on homogeneous interference problems, including studies on wireless LAN resource management and control technologies based on centralized WLAN architectures, anti-interference techniques based on channel allocation methods, and related research on interference assessment methodologies. While these studies demonstrate considerable foresight and innovation, they fail to fully address homogeneous interference issues in high-density Wi-Fi deployment environments. First, such application scenarios demand high scalability, and as wireless network node scale increases, homogeneous interference problems—such as channel conflicts among neighboring Wi-Fi devices—occur with dramatically increased frequency. Moreover, homogeneous interference conditions become more complex and difficult to accurately assess due to scale and density effects. Finally, public venues with concentrated users are relatively sensitive to network service reliability but less sensitive to homogeneous interference. Therefore, operations that cause Wi-Fi service outages, such as channel reallocation, should be avoided.

High-density Wi-Fi deployment environments present two key challenges for homogeneous anti-interference strategies: (a) Wi-Fi devices struggle to use channels and other network resources in an orderly fashion. On one hand, due to the blindness of individual device channel allocation strategies within the overall wireless LAN, channel adjustments can trigger domino effects that exacerbate homogeneous interference problems. On the other hand, given the large scale and need for flexible expansion of wireless LANs, achieving unified and orderly management is difficult; managing large-scale distributed clusters requires complex and effective scheduling mechanisms that consume valuable bandwidth resources and create server node bottlenecks. These requirements conversely limit wireless LAN scale due to cost constraints. (b) Wi-Fi devices struggle to accurately assess homogeneous interference and its network impact. As shown in Figure 1 [Figure 1: see original paper], Wi-Fi devices are constrained by performance and basic architecture limitations that prevent accurate signal and spectrum analysis of the external environment. Furthermore, as illustrated in the Wi-Fi deployment environment schematic in Figure 2 [Figure 2: see original paper], Wi-Fi devices operating at signal coverage edges become the norm in high-density environments, and according to literature, enclosed indoor spaces and wall structures cause signal reflection, diffraction, and penetration losses, further increasing the difficulty of interference degree assessment. In summary, high-error interference assessment results and blind, disordered anti-interference strategies cannot effectively enhance anti-interference capability in high-density Wi-Fi device environments.

1 Related Work

Current research exists on homogeneous interference measurement, Wi-Fi channel allocation, and Wi-Fi anti-interference mechanisms. Regarding wireless network performance under interference conditions, literature elaborates on using the SINR model to evaluate and constrain wireless LAN optimization algorithms. SINR is a ratio model of useful signal to interference and noise, where S represents useful signal strength, I represents interference signal strength, and N represents noise signal strength. The SINR model evaluates wireless network performance through three dimensions but does not consider the impact of Wi-Fi device load levels.

In literature, He Yuan et al. categorize 2.4 GHz homogeneous interference as one of the wireless protocol coexistence problems, systematically elaborating and analyzing the causes, impacts, and research progress of related technologies for coexistence issues. They also discuss three coexistence technical approaches under homogeneous interference environments: avoidance, tolerance, and concurrent transmission. Avoidance coexistence technology avoids interference from temporal and frequency dimensions through multi-channel techniques. Tolerance coexistence technology increases tolerance to homogeneous interference and avoids transmission efficiency degradation by applying the capture effect. Concurrent transmission coexistence technology is essentially a tolerance phenomenon of physical layer multipath effects, improving network performance by enhancing packet reception rates.

Literature describes IoT technology research based on centralized WLAN architecture for unified wireless network resource management. However, the Access Controller (AC) in WLAN systems becomes a bottleneck limiting scale and scalability. Moreover, complex management, communication, and security mechanisms consume valuable bandwidth resources, which is unacceptable for the 4 M, 8 M, and 10 M wired bandwidth commonly found in practical application scenarios. Literature proposes a client-driven and conflict-set coloring-based wireless channel management method. Although this method can effectively mediate homogeneous channel conflicts, its management and use of channel resources remain disordered.

This paper designs a 4D interference degree evaluation model that, compared to SINR, incorporates device load as an important dimension for assessing interference impact and redesigns the calculation models for noise, useful signals, and interference based on Wi-Fi device characteristics. Additionally, a gain expectation model is designed to orderly schedule performance resources through an optimal adjustment plan, enhancing tolerance during signal transmission. Finally, a consistent hash algorithm is improved to complete channel resource reallocation through weight-based pairing with progressively decreasing channel intervals, synchronizing allocation results across devices to ensure adjacent Wi-Fi devices avoid occupied channel resources.

2 Interference Degree Assessment Model

2.1 Analysis of Homogeneous Interference Problems in High-Density Wi-Fi Deployment Environments

This section analyzes homogeneous interference problems in high-density Wi-Fi deployment environments through experiments and investigations. First, experimental results mentioned in literature exemplify the relationship between Wi-Fi interference and channel quality. As shown in Figure 3 [Figure 3: see original paper], channel quality varies dramatically under interference conditions, and higher Wi-Fi rates result in poorer channel communication quality. Literature elaborates on Wi-Fi performance assessment methods for wireless LANs, demonstrating that metrics such as packet loss rate, throughput, bit error rate, and network delay correlate with Wi-Fi performance and interference degree. Literature describes using the PRR-SINR model to evaluate wireless LAN signal interference, explicitly identifying packet reception rate (PRR) as an important metric for measuring interference degree.

Furthermore, experiments analyze the impact of homogeneous signal interference on Wi-Fi wireless network quality and interference characteristics. Figure 4 [Figure 4: see original paper] presents statistical results of high-quality connection counts and wireless bandwidth loss degrees when neighboring Wi-Fi devices share channel resources, where high-quality connections are defined as active connections capable of occupying at least 150 kB of bandwidth. The results show that Wi-Fi load capacity is affected by interference–the stronger the interference, the lower the load capacity and the poorer the network service provided. Moreover, wireless bandwidth loss rate exhibits strong correlation with packet loss rate; higher packet loss rates correspond to greater bandwidth loss rate values.

Analysis results indicate: (1) Communication quality varies significantly across different channels, and homogeneous interference affects device load capacity. When interference degree is greater and device load connection numbers are higher, Wi-Fi device wireless network service quality deteriorates, necessitating that devices with more load users obtain better quality channels. (2) In high-density Wi-Fi deployment environments, stronger homogeneous signal interference causes greater wireless bandwidth loss due to interference. Additionally, packet loss rate, bit error rate, network delay, and background noise all exhibit strong correlation with homogeneous interference degree. Therefore, this paper proposes a Wi-Fi interference degree assessment model that combines multiple dimensional metrics to measure homogeneous interference degree in high-density Wi-Fi deployment environments.

2.2 Interference Degree Assessment Model

Based on the analysis conclusions in Section 2.1, interference degree exhibits strong correlation with bandwidth loss, network quality, signal noise, and device load. To accurately assess homogeneous interference in high-density Wi-Fi deployment environments, the interference degree assessment model combines four dimensions, termed the 4D Interference Assessment Model.

Wireless network bandwidth loss relative to wired network bandwidth can represent network performance loss caused by homogeneous interference. For convenience, this is defined as interference loss. Packet loss rate, bit error rate, and network delay are effective indicators for evaluating network communication quality. This paper uses these three indicators to comprehensively describe current communication states, defined as communication level for convenience. Wi-Fi device load connection numbers are dynamic, and maximum load capacity is constrained by device performance. This paper uses the ratio of current load connection numbers to maximum load connection numbers in design specifications as the core indicator for evaluating load state, defined as load level for convenience. Scene noise is an important indicator affecting interference degree. This paper uses the average strength of co-channel Wi-Fi signals to describe background noise intensity, defined as noise level for convenience.

Let $\mathcal{U}_{wired}^{T}$ be the vector of wired bandwidth (Mbps) values collected with period

T, and $\mathcal{U}_{wireless}^{T}$ be the vector of wireless bandwidth (Mbps) values collected with period T. Let $||\mathcal{U}_{wired}||$ and $||\mathcal{U}_{wireless}||$ denote the counts of collected wired and wireless bandwidth (Mbps) values, respectively.

Definition 1 (Interference Loss). Let $n_{wireless}$ be the number of valid bandwidth data points collected within period T. Then interference loss is defined as:

$$P_U = \frac{\sum_{i=1}^{n_{wireless}} u_{wired,i}}{\sum_{i=1}^{n_{wireless}} u_{wireless,i}}$$

Let $\mathcal{T}_{delay}^{T}$ be the vector of network delays collected with period T, $||\mathcal{T}_{delay}||$ denote the count of collected network delay data points, $\mathcal{U}_{biterr}^{T}$ be the bit error rate collected with period T, and $\mathcal{U}_{loss}^{T}$ be the packet loss rate collected with period T.

Definition 2 (Signal Level). Let C_{delay} be the network delay constant representing the minimum acceptable network delay in milliseconds (ms). Then signal level is defined as:

$$S = \frac{\sum_{i=1}^{||\mathcal{T}_{delay}||} f(C_{delay} - T_{delay,i})}{\sum_{i=1}^{||\mathcal{T}_{delay}||} C_{delay}} \times \left(1 - \frac{\sum_{i=1}^{||\mathcal{T}_{delay}||} \mathcal{U}_{biterr,i}}{||\mathcal{T}_{delay}||}\right) \times \left(1 - \frac{\sum_{i=1}^{||\mathcal{T}_{delay}||} \mathcal{U}_{loss,i}}{||\mathcal{T}_{delay}||}\right)$$

where $f(x,y) = \begin{cases} x - y & \text{if } x - y < 0 \\ 0 & \text{if } x - y \geq 0 \end{cases}$.

Let $\mathcal{U}_{conn}^{T}$ be the vector of online connection counts collected with period T, and $||\mathcal{U}_{conn}||$ denote the count of collected online data points.

Definition 3 (Load Level). Let C_{conn} be the device load connection number upper limit. Then load level is defined as:

$$G = \frac{\sum_{i=1}^{||\mathcal{U}_{conn}||} \mathcal{U}_{conn,i}}{C_{conn}} \times 100$$

Let $\mathcal{U}_{noise}^{T}$ be the vector of noise signal strengths collected with period T (in dBm), and $\mathcal{U}_{signal}^{T}$ be the vector of device signal strengths collected with period T (in dBm). Let $||\mathcal{U}_{signal}||$ denote the count of collected device signal strength data points, and $||\mathcal{U}_{noise}||$ denote the count of collected noise signal strength data points.

Definition 4 (Noise Level). Noise level is defined as:

$$N = \frac{\sum_{i=1}^{||\mathcal{U}_{noise}||} \mathcal{U}_{noise,i} \times \sum_{i=1}^{||\mathcal{U}_{signal}||} \mathcal{U}_{signal,i}}{||\mathcal{U}_{noise}|| \times \left(\sum_{i=1}^{||\mathcal{U}_{noise}||} \mathcal{U}_{noise,i} + \sum_{i=1}^{||\mathcal{U}_{signal}||} \mathcal{U}_{signal,i}\right)}$$

The core metric of the 4D interference degree assessment model is the ratio of wireless network quality to homogeneous interference impact, which can accurately reflect causal relationships in interference environments:

$$\text{WINLR} = \frac{S}{P_U \times G \times N}$$

3 "Tolerance + Avoidance" Anti-Interference Strategy

3.1 Tolerance Strategy

The tolerance strategy is a resource scheduling approach that enhances signal transmission tolerance by orderly adjusting three Wi-Fi performance resources: signal strength, bandwidth, and device load. This paper designs a mathematical model to calculate the expected gain from Wi-Fi resource adjustments, providing a basis for selecting an optimal resource scheduling plan.

Since homogeneous interference conditions experienced by a Wi-Fi device within period T remain constant, let the interference degree at this time be WINLR_{tmp}. Let the estimated interference degree after tolerance strategy adjustment be WINLR_{eval}. Then the strategy adjustment gain is:

$$\Delta\text{WINLR} = \text{WINLR}_{eval} - \text{WINLR}_{tmp}$$

The tolerance strategy anti-interference module comprises three independent components: signal strength adjustment, bandwidth adjustment, and device load adjustment. Let $\Delta\text{WINLR}_{signal}$ be the gain obtained from signal strength adjustment, $\Delta\text{WINLR}_{width}$ from bandwidth adjustment, and $\Delta\text{WINLR}_{load}$ from load limit adjustment. The expected anti-interference gain from the tolerance strategy is defined as:

$$E[\Delta\text{WINLR}] = P_{signal} \times \Delta\text{WINLR}_{signal} + P_{width} \times \Delta\text{WINLR}_{width} + P_{load} \times \Delta\text{WINLR}_{load}$$

where P_{signal}, P_{width}, and P_{load} are the probabilities of each adjustment strategy, satisfying $P_{signal} + P_{width} + P_{load} = 1$ and $P_{signal} > P_{width} > P_{load}$.

The adjustable space for signal strength and bandwidth can be represented as $[x_{Tmp}, x_{Max}]$ and $[y_{Tmp}, y_{Max}]$, where x_{Max} and y_{Max} are Wi-Fi device rated performance indicators and x_{Tmp} and y_{Tmp} are current values. If C_{act} is set as the threshold for network usage by wireless access connections, then the number of inactive connections constitutes the adjustable space for device load: $\mathcal{U}_{sleep} = \{U_i | U_i^{sleep} < C_{act}\}$, where U_i^{sleep} represents the number of sleep connections.

Therefore, the tolerance strategy can be defined as: Let x be signal strength, y be bandwidth, and z be device load. For all $x \in [x_{Tmp}, x_{Max}]$, $y \in [y_{Tmp}, y_{Max}]$, and $z \in [0, \mathcal{U}_{sleep}]$, the optimal performance resource scheduling plan (x, y, z) that satisfies $E[\Delta\text{WINLR}(x, y, z)] - E[\Delta\text{WINLR}(x', y', z')] > 0$ is the tolerance strategy.

3.2 Avoidance Strategy

The avoidance strategy improves the consistent hash algorithm to coordinate channel resource allocation and result synchronization within the interference space. This strategy enables each Wi-Fi device participating in channel allocation to maintain an identical consistent hash ring space, as shown in Figure 5 [Figure 5: see original paper], effectively avoiding complex communication processes for synchronizing allocation results.

Additionally, weights are assigned to channel resources and device loads, biasing channel adjustment results toward enabling Wi-Fi devices with heavier workloads to obtain higher-quality channel resources. As shown in Figure 6 [Figure 6: see original paper], the avoidance strategy searches clockwise and allocates appropriate channel resources weighted by resource quality to Wi-Fi devices.

The avoidance strategy adheres to strict conflict avoidance rules: adjacent Wi-Fi devices must maintain safe channel spacing when obtaining channel resources, with both co-channel occupation and adjacent-channel usage considered channel allocation conflicts. As shown in Figure 7 [Figure 7: see original paper], Wlan1 has co-channel conflict with Wlan2, adjacent-channel conflict with Wlan3, and appropriate channel allocation with Wlan4, which is two channel intervals away.

4 Anti-Interference Mechanism WifiAAS for High-Density Wi-Fi Deployment Environments

4.1 WifiAAS Interference Detection Module

This section introduces the design and workflow of WifiAAS’ s interference detection module and strategy scheduling module.

WifiAAS borrows concepts from literature but adopts a Wi-Fi device self-centered interference analysis model and uses packet reception rate (PRR) from literature to calculate communication range and interference index. If node v_i in wireless LAN $\mathcal{N}_v$ experiences homogeneous co-channel interference from neighboring wireless LAN $\mathcal{N}_u$ node u_j, then the interference index produced by neighbor wireless LAN $\mathcal{N}_u$ on v_i is:

$$I(u_j, v_i) = \frac{|\{v_k|(v_k, v_i) \in \mathcal{D}_v \wedge v_k \in \mathcal{N}_u\}|}{|\mathcal{N}_v|}$$

where $\mathcal{D}_v$ represents the circular Wi-Fi signal coverage range with radius $R^+_{v_i}$, and nodes within $R^+_{v_i}$ are assumed to be interfered by node v_i. $R^+_{v_i}$ is the space region where packet reception rate (PRR) satisfies a certain constant. Node v_i broadcasts X_{probe} Beacon probe packets, and the space range where PRR exceeds a threshold is considered the interference-affectable domain.

Due to the spatial locality principle of homogeneous interference generation in wireless LANs and the mutual nature of interference between nodes, we can set

$j = i$ and $|\mathcal{N}_u| = |\mathcal{N}_v|$. If wireless LAN $\mathcal{N}_j$ represents the set of all interfered nodes in a local interference event with total node count k_j, then the interference index produced by wireless LAN $\mathcal{N}_j$ on node v_i is:

$$I(u_j, v_i) = \frac{\sum_{u \in \mathcal{N}_j} I(u, \mathcal{N}_j)}{|\mathcal{N}_j|}$$

The homogeneous signal interference experienced by the entire wireless LAN can be defined as:

$$\text{WINLR} = \sum_{j \in \mathcal{N}} I(u_j, \mathcal{N})$$

WifiAAS' s anti-interference strategy first uses the interference detection module to periodically detect and statistically analyze WINLR, reflecting interference conditions experienced by Wi-Fi devices within period T and assisting the scheduling module in flexibly employing tolerance and avoidance strategies. The specific workflow for interference detection and strategy scheduling is:

a) When the interference detection module discovers through periodic detection that the WINLR metric exceeds threshold WINLR_{thr1}, the scheduling module broadcasts the result appended to probe packets to surrounding devices, changes device status to "interfered," and begins receiving probe packets from other devices. Simultaneously, the strategy scheduling module initiates the tolerance anti-interference strategy to improve current homogeneous interference conditions.

b) The interference detection module collects WINLR metrics from other interfered Wi-Fi devices within the period and statistically analyzes the homogeneous signal interference WINLR_{air} of the wireless LAN composed of the "interfered" device set. When detection reveals that the WINLR_{air} metric exceeds threshold WINLR_{thr2}, the scheduling module stops using the tolerance anti-interference strategy, adds the periodically collected probe packet attribution list and window agreement to broadcast packets.

c) The strategy scheduling module parses and statistically analyzes the intersection of attribution lists collected during the fixed window period as the coordination object list for the avoidance mechanism and submits it to the avoidance anti-interference strategy module.

4.2 Tolerance Strategy Anti-Interference Module

This section describes the core workflow of the tolerance strategy anti-interference module:

a) The tolerance strategy module begins waiting for detection results from the interference detection module. When detection period T ends, the tolerance strategy module uses period $T+1$ as the strategy gain estimation period and adopts the WINLR metrics from period T as the WINLR_{tmp} for period $T+1$.

b) The tolerance strategy module collects adjustable space for strategies during period $T+1$, then estimates the anti-interference gains from signal strength adjustment, bandwidth adjustment, and device load adjustment within their respective adjustable spaces, substituting them into the anti-interference gain mathematical expectation model for calculation.

c) The tolerance strategy module sets the strategy combination with the highest anti-interference gain mathematical expectation as the executable strategy and implements this strategy during period $T+1$.

4.3 Avoidance Strategy Anti-Interference Module

This section introduces the algorithm design of the avoidance strategy anti-interference module. Both channel resource weight and device load weight in the avoidance strategy are three-level: the top 30% of channel resources with the lowest idle rate have weight 3, the next 50% have weight 2, and the final 20% have weight 1; Wi-Fi devices with load rates above 80% have weight 3, those with load rates 80% but >40% have weight 2, and those below 40% have weight 1.

Algorithm 1: Automatic Channel Coordination and Allocation Algorithm

Input: `list_device` (device id, load weight, old channel id), `list_channels` (channel id, resource weight)
Output: `list_result` (device id, new channel id)

```
1. Yhash(list_channels); // Load all available channel resources into the consistent hash ring space
2. for (i=0; i<len(list_devices); i++) {
    • Yhash(device); // Calculate device position in consistent hash ring space
3. for (j=current; j<len(list_channels); j++) {
    • if (device_hash <= channel_hash) {
        – if (device_weight >= channel_weight) {
            ∗ list_result.append((device_id, channel_id));
        – } /*if*/
    • } /*if*/
    • } /*for*/ // Search clockwise in consistent hash space from current position for appropriate channel, allocating high-resource-weight channels to heavy-load devices
4. if (Pairing failure) {
    • for (j=0; j<len(list_channels); j++) {
        – if (device_hash <= channel_hash) {
            ∗ if (device_weight >= channel_weight) {
```

```
                · list_result.append((device_id, channel_id));
              ∗ } /*if*/
          – } /*if*/
      • } /*for*/
      • } /*if*/ // If allocation fails, restart clockwise search from origin
        position in consistent hash space
5. load(list_result) // Load all completed channel allocation results
6. for (row in list_result) {
      • if (device.channel - near_device.channel <= interval) {
          – remove(conflict_channelid);
          – goto step 3;
      • } /*if*/
      • else {
          – return True;
      • } /*if*/
      • } /*for*/ // Traverse allocation results; if adjacent device channel
        spacing is less than constant interval, consider allocation conflict and
        remove conflicting channel node from consistent hash space, then
        return to step 3 for reallocation
7. if (Conflict coordination failure) {
      • interval = interval - 1;
      • goto step 6;
      • } /*if*/ // If channel allocation conflict coordination fails, decrease
        channel interval constant and return to step 6 for re-coordination
8. return list_result; // Return final channel allocation results
```

Algorithm 1 employs a consistent hash ring space, enabling all devices participating in channel allocation to obtain consistent channel allocation results with high coordination. This approach effectively eliminates complex communication processes and long communication cycles for synchronizing allocation results among Wi-Fi devices, substantially reducing algorithm convergence time. Additionally, the algorithm strongly avoids interference from adjacent channels by removing conflicting channels and reassigning them, further enhancing the anti-interference effect of channel allocation. Due to space limitations, detailed algorithm descriptions are omitted.

5 WifiAAS Performance Evaluation

This chapter first validates the effectiveness of the WifiAAS strategy through real deployment scenario testing and verifies its anti-interference performance through comparative experiments with commercial Wi-Fi devices. Then, simulation experiments test the convergence performance of WifiAAS in high-density Wi-Fi deployment environments.

5.1 Real Deployment Scenario Evaluation

This section validates WifiAAS strategy performance through real deployment testing. The test site is located on the 12th floor of Fuhai Building, with a room structure similar to hotel compartments and restaurant cubicles. Within the test space, Wi-Fi signals from other offices and even other floors can be detected, with the actual deployment environment signal conditions shown in Figure 10 [Figure 10: see original paper]. The test space is a 10 m² meeting room. The test machine wlan1 connects via LAN cable to a desktop serving as a test server, while one laptop and four mobile phones serve as Wi-Fi device loads, accessing network services provided by test machine wlan1 through wireless connections. Additionally, a commercial device wlan2 without the WifiAAS strategy is installed in the test space, connected to the test server and mobile devices in the same manner. The test environment network topology is shown in Figure 11 [Figure 11: see original paper], with relevant experimental parameters listed in Table 1 .

Table 1: Experimental Parameters | Device Name | Test Machine wlan1 | Commercial Device wlan2 | |———-|————-|—————| | System | Openwrt | Openwrt | | Load Device Count | 5 | 5 | | Anti-Interference Mechanism | WifiAAS | None |

5.2 Throughput Analysis

Throughput is a key metric for measuring network communication quality. This section focuses on analyzing the impact of homogeneous signal interference on Wi-Fi device throughput, where throughput refers to end-to-end throughput —the average data volume of data packets forwarded by test machine wlan1 received by the test server per unit time.

To test interference impact on throughput, the Loadrunner tool is used for throughput testing. Figures 12 Figure 12: see original paper and (b) present average throughput trends for the experimental and control groups. The results show that test machine wlan1' s throughput remains higher than commercial device wlan2' s throughput throughout the test, with wlan2' s throughput trend decreasing over time. Although wlan1' s throughput fluctuates to varying degrees, it remains basically stable at a high level.

Figures 13 Figure 13: see original paper and (b) show throughput trends under strong homogeneous interference. Both experimental and control groups exhibit dramatic fluctuations, but test machine wlan1 maintains a stable and rising wireless network throughput under WifiAAS, while commercial device wlan2 shows a continuously low trend after severe vibration, particularly experiencing a brief wireless network service interruption. The network service interruption causes Wi-Fi device restart, after which the commercial device randomly selects a new channel, resulting in a sharp throughput increase.

Therefore, the conclusion can be drawn: when Wi-Fi devices experience interference, the WifiAAS strategy can effectively improve anti-interference capability and significantly enhance Wi-Fi throughput, thereby protecting users' wireless network quality under interference conditions.

5.4 Convergence Analysis

When homogeneous interference occurs, the channel coordination algorithm of WifiAAS' s avoidance strategy coordinates all interfered devices in the wireless LAN to perform a series of channel allocation, coordination, and switching operations. The time convergence of the avoidance strategy is also an important metric for evaluating Wi-Fi anti-interference mechanisms. To assess WifiAAS convergence performance, three high-density Wi-Fi deployment simulation scenarios are deployed (4-node, 8-node, and 10-node), and the average time from channel adjustment initiation to completion of channel switching across all interfered nodes is statistically analyzed.

Figure 15 [Figure 15: see original paper] presents the arithmetic mean of channel coordination time consumption across 20 Wi-Fi device coordination runs for the three simulation scenarios. The results show that as node numbers increase, participating avoidance strategy nodes increase, leading to longer convergence times. However, when total wireless LAN nodes exceed 4, due to spatial limitations on signal coverage, homogeneous interference exhibits spatial locality, causing the number of nodes participating in the avoidance strategy to decrease sharply. Consequently, wireless LAN avoidance strategy convergence time hovers around 35 seconds. These results demonstrate that WifiAAS' s channel avoidance strategy exhibits good convergence performance, and increasing wireless LAN scale does not cause substantial convergence time extension.

WifiAAS also incurs certain storage space and communication overhead. To accurately obtain WifiAAS communication status, tcpdump monitoring and analysis tools are installed on test machine wlan1 to statistically analyze the total number of average communication packets per channel adjustment. WifiAAS communication information includes channel adjustment notifications, device lists, and interference degree detection reports. The average control packet count is 26.72, and this number increases multiplicatively with more coordinated devices. In large-scale networking scenarios, WifiAAS requires stricter control communication mechanisms to reduce redundant communication processes. However, in real high-density Wi-Fi deployment environments, interference events requiring channel coordination are often localized, and statistical analysis shows that daily channel coordination needs are infrequent. Therefore, WifiAAS communication overhead is acceptable.

Regarding memory and CPU resource usage, analysis and statistics from top logs reveal that WifiAAS resource consumption never exceeds 10% for either resource type, with no memory leakage issues. Furthermore, as shown in Figure 14 [Figure 14: see original paper], WifiAAS strategy occupies 31.2 KB of flash ROM space, which is higher than FixChnl and ARCH mechanisms. However, current commonly used Wi-Fi device platforms provide 126 KB RAM and 16 MB flash ROM, making storage usage below 1 MB acceptable. After UPX compression, WifiAAS executable program size reduces to 61.1%, further reducing flash ROM resource usage without sacrificing performance.

6 Conclusion

Addressing homogeneous interference problems in high-density Wi-Fi deployment environments, this paper proposes a 4D interference degree assessment model and a "tolerance + avoidance" anti-interference strategy, implementing an anti-interference mechanism called WifiAAS. WifiAAS first uses its interference detection module to periodically detect WINLR of Wi-Fi devices based on the built-in 4D interference degree assessment model and reports status information. The scheduling module then evaluates maximum gain adjustments to the tolerance strategy to offset network impact caused by interference. Finally, when the local wireless LAN space is in an interference state, the scheduling module employs a decentralized distributed architecture-based avoidance strategy to achieve orderly and rational channel resource allocation, enabling heavy-load Wi-Fi devices to obtain higher-quality channel resources and thereby enhancing wireless LAN anti-interference capability and network performance in dense environments.

Experimental validation demonstrates that: (a) In high-density Wi-Fi deployment environments, WifiAAS can provide corresponding high-quality channel resources for interfered Wi-Fi devices, mediate homogeneous interference problems, and improve throughput and network performance; (b) Under identical interference conditions, Wi-Fi devices with built-in WifiAAS can orderly use wireless resources based on interference degree, achieving better network performance and throughput; (c) WifiAAS does not introduce excessive communication or storage overhead. Therefore, experimental verification of WifiAAS confirms the effectiveness of the proposed 4D interference degree assessment model and "tolerance + avoidance" anti-interference strategy.

The "tolerance + avoidance" anti-interference strategy demonstrates strong applicability for indoor wireless LAN scenarios with dense Wi-Fi devices and large scales, such as large conference venues, commercial districts, and hotels. However, for wireless LANs with high management control and security requirements, the strategy' s resource management capabilities remain incomplete. Future work will integrate the "tolerance + avoidance" anti-interference strategy with adaptive LAN technologies to further improve the strategy and meet big data IoT requirements for adaptive, intelligent, and sensing networks.

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Note: Figure translations are in progress. See original paper for figures.