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## Fair Resource Allocation in Wi-Fi Networks

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# Democratic Wireless Channel Assignment: Fair Resource Allocation in Wi-Fi Networks

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***User experience is the ultimate quality of service criterion for modern WLAN networks. However, network configuration approaches are mainly network-centric. We envision a paradigm shift, empowering users in network management. We study how automated negotiation and collective intelligence can support the democratic configuration of a wireless network, leveraging client and provider interests. This new paradigm allows for flexible network configuration, which enables better exploitation of resources considering the clients' real usage and needs, and a fair distribution of throughput among users.***

The development of the digital economy requires democratizing access to value-added digital services. These services are available through cellular and wired networks, but to close the gap we need high-performance, low-cost wireless local area networks (WLAN) in most areas. The current technology—the family of IEEE 802.11 standards, commercially known as Wi-Fi—aims to bring together ubiquity and low cost.

Despite the latest expansions of the Wi-Fi frequency spectrum, with the recent opening of the 6 GHz band for use by Wi-Fi 6E[1] and soon by Wi-Fi 7,[2] the growing demand for services and the exponential increase in wireless devices will saturate the spectrum and result in under-utilization of the future WLAN networks. Mechanisms for enhancing spectrum usage efficiency, along with techniques that enable a fairer distribution of bandwidth, would greatly facilitate democratizing access to services.

*Channel selection*, i.e., selecting channels (frequencies) where Wi-Fi access points (APs) operate, is a key factor determining the spectrum usage efficiency. Typically, channel selection procedures try to choose the channel where the interference is minimum, and the signal to interference plus noise ratio (SINR) is maximised.

Maximizing SINR entails obtaining the best throughput. There is a wide variety of techniques in the literature and industry for channel selection, but all of them suffer from the same limitation: they address the problem from the network's point of view. That is, most techniques try to minimize interference between APs without considering issues relevant to end-users such as client location and network usage. A few techniques take clients into account but give them a passive role. For instance, popular implementations for channel assignment[3] consider the number of clients associated with each AP but ignore their specific location or network usage. Further, the decision is made unilaterally and statically.

We take an innovative perspective on channel assignment by shifting the decision power to the clients, since they are the ones ultimately receiving the impact of the decision. To this end, we propose and evaluate two client-centric channel assignment approaches, where clients play an active role in decision making. Our experiments show promising results in both social welfare and fairness, which leads us to believe this paradigm shift


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opens new opportunities to enable better and fairer resource allocation.

## CHANNEL SELECTION IN WLANS

The popular operating mode in current WLANs is the infrastructure mode. In this mode, there are two kinds of devices: APs and stations (STAs). STAs (e.g., smartphones and laptops) provide wireless connectivity to end users. Each STA is wirelessly attached to an AP, which connects the STA to the rest of the network. Each AP is configured with a wireless channel, and all its STAs use that channel. Perhaps, the AP-centric behavior motivated early efforts in WLAN channel selection to neglect the presence of STAs.[4]

Later, some works[5] proved that considering STAs in channel selection leads to more efficient wireless networks since STAs are responsible for a great number of interfering signals. However, this greatly increases the complexity of the problem, as the number of STAs is notably higher than the number of APs. Therefore, the tendency was to perform centralized channel assignment (relieving the APs from the complexity) or to resort to simple distributed heuristics. In fact, a popular channel selection algorithm—least congested channel search (LCCS)—takes STAs into account in a simplistic manner. In LCCS, each AP counts the number of detected STAs in each possible channel and chooses the channel with the minimum number. Although more complex channel selection algorithms provide better performance,[6,7] LCCS remains widespread due to its simplicity. Thus, any proposed channel selection algorithm must match the simplicity of LCCS, and consider STAs.

## MAKING INTERNET ACCESS FAIRER: DESIGN PRINCIPLES, OPPORTUNITIES, AND CHALLENGES

As LCCS shows, limiting complexity is important for channel selection. Complexity is an important criterion for two reasons. First, the number of STAs is expected to increase exponentially since the latest IEEE 802.11 standards intend to accommodate a huge number of wireless STAs,[8,9] enabling dense and ultra-dense Wi-Fi deployments.[10] Second, channel selection will be more complex due to the multiband features included in IEEE 802.11be (the future Wi-Fi 7).

As discussed earlier, considering STAs enables more efficient channel selection.[11] However, unlike previous approaches, we claim that the inclusion of STAs in channel selection must be *active*. That is, STAs should actively *participate* in channel selection. This active role enables STAs to consider their preferences and reach fair configurations. As the final objective of networks is to provide a high quality of experience to STAs, why not have them participate in the process?

The active participation of STAs in channel selection opens a new world of opportunities. For example, it accounts for diversity. In a connected digital world, not only the number of STAs, but also the types of STAs, will increase. As different types of devices will have different needs, it is crucial to develop channel selection techniques that account for this diversity. Traditionally, the best channel has been considered as the one that offers the highest throughput. However, in high-diversity settings (as future WLANs will have), other performance metrics can be more important. For example, an STA may be interested in the channel where it is able to have greater coverage (e.g., to allow for greater mobility) and another STA may be interested in the channel where its energy consumption is the lowest (e.g., if it is running low on battery). It is important to note the trend that future WLAN networks (Wi-Fi 7) will operate in several frequency bands (2.4, 5, and 6 GHz). So, the effect of channel selection will have an impact not only on throughput but also on a richer set of performance metrics like coverage or energy efficiency. We propose the active participation of STAs in channel selection as a suitable way to consider high-diversity wireless networks.

Obviously, involving end users in important network decisions like channel selection involves risks and challenges. For example, as channel selection becomes a distributed procedure among the STAs belonging to the same AP, we must ensure that an STA or a group of STAs cannot deviate from the expected rules and alter the process to have a negative impact on the performance of other STAs. Another important challenge is to avoid STA impersonation attacks since they would alter the democratic channel selection procedure. An even more complex challenge is to avoid collusion between STAs to influence the channel allocation procedure (keep in mind that a single user could have several STAs in a network). This is related to strategic stability and incentive compatibility, which we successfully addressed in previous work.[12]

We propose two client-based channel selection algorithms aiming to improve the performance over the LCCS algorithm but which are simple enough to implement and adopt. Our proposal can form a basis for other client-based procedures, opening the door to the application of scientific disciplines such as automated negotiation, collective intelligence,[13] crowd-scale deliberation,[14] and game theory.[15]

## DEMOCRATIC PARTICIPATION IN NETWORK SETUP

Our first proposal, *direct channel voting* (DCV), is inspired by the idea of democratic decision-making. In

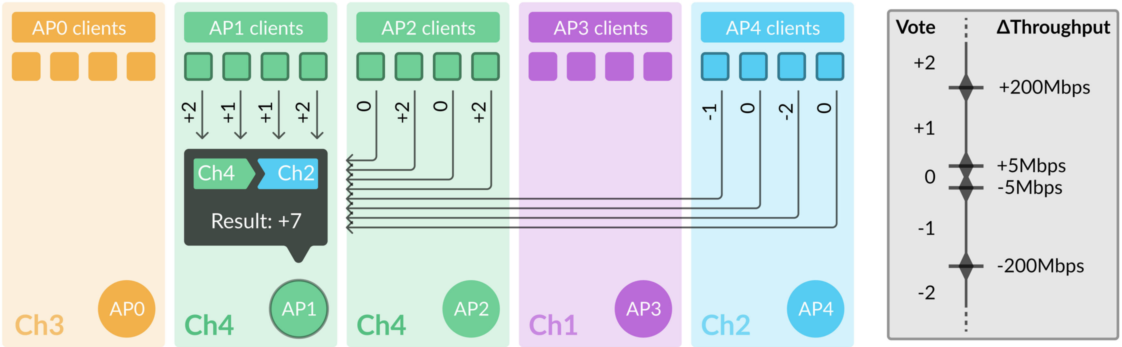


**FIGURE 1.** Negotiation bid and valuation example: AP1 proposes switching from channel 4 (green) to channel 2 (blue).

DCV, the APs periodically hold *elections*, where the STAs vote for the preferred channel considering their individual quality of experience metrics. Without loss of generality, in this article, we have considered as the utility for each STA the estimated throughput, which is determined by the SINR. To avoid unnecessary channel switches, STAs vote for their current channel in case there is a tie between that and other preferred channels. The AP acts as the trustee and selects the channel with the highest number of votes, breaking ties randomly.

## NEGOTIATION AMONG THE NETWORK ACTORS

Our second proposal for active participation of STAs in channel selection is automated negotiation, with the advantage of being more suitable to address strategic behavior. We have successfully used negotiation techniques for channel assignment, but always with a provider-centric approach, where the Internet Service Providers deploying the APs were the negotiating agents.

As a first step in client-centric negotiation, we propose a *mediated negotiation* approach, where the clients affected by a potential channel change (i.e., the ones whose channel either interfere with the old channel or with the new one) participate in the negotiation. The approach is inspired in our proposal,[11] where agents representing ISPs evaluated contracts offered by a mediator by iteratively mutating an initial random contract. In contrast, here agents represent the final clients and perform fine-grained valuations of the contracts using the five integer possibilities in the $[-2, 2]$ interval.

Figure 1 shows an example of bidding and evaluation during the negotiation process, where AP1, acting as a mediator, proposes to switch from channel 4 (green) to channel 2 (blue). We can see that only clients affected by the change (i.e., already operating in one of the two relevant channels) emit valuations. These valuations are issued depending on their perceived utility variation for the change. For illustration, we have chosen the thresholds shown in Figure 1 for the valuations of all agents. A negotiation round includes the valuation of all bids involving changing the agent where the AP acting as the mediator operates (in this case, AP1). After all affected agents have given valuations for all the alternatives, the AP chooses the one with the greatest support. A different AP is chosen as a mediator for the next negotiation round. The negotiation ends after a fixed number *N* of rounds or after convergence, defined as a number *m* of rounds without a change.

## EVALUATION AND RESULTS

We evaluate our proposals by comparing them with the standard LCCS technique. We perform the evaluation in a Wi-Fi 6 (IEEE 802.11ax) dense residential environment. We use Orthogonal Frequency Division Multiplexing with one spatial stream in the 5 GHz frequency band with 80 MHz channels, as it is common in this technology. With this configuration, and with a guard interval of 1.6 $\mu$s, the set of Modulation and Coding Schemes (MCS) provides a throughput from 34 Mbit/s (MCS0) to 567.1 Mbit/s (MCS11).

Our experimental setting resembles a five-floor building with eight flats per floor. In each of the 40 flats, there is one AP and eight STAs attached to it (for a total of 320 STAs). All clients are set up to prefer the channel with the highest SINR.

Table 1 summarizes the main results, showing the average performance of the different STAs and their distance to their AP. The last column shows the average individual utility (average throughput per STA in

**TABLE 1.** Average STA utility (i.e., throughput) in Mbit/s (Th) and Jain fairness index (F) for different distances from STA to AP.

| Distance to AP (m) | 0-2 | | 2-4 | | 4-6 | | 6-8 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Th | F | Th | F | Th | F | Th | F | |
| LCCS | 485.72 | 0.9926 | 477.05 | 0.9877 | 432.06 | 0.9681 | 345.68 | 0.914 | |
| Voting | 503.18 | 0.9978 | 496.54 | 0.9947 | 468.69 | 0.9842 | 370.12 | 0.9322 | |
| Negotiation | 504.53 | 0.9989 | 491.76 | 0.9939 | 461.02 | 0.9815 | 371.92 | 0.9261 | |
| Distance to AP (m) | 8-10 | | 10-12 | | 12-14 | | 14-16 | | All distances (avg. utility) |
| | Th | F | Th | F | Th | F | Th | F | |
| LCCS | 253.68 | 0.7819 | 156.68 | 0.6723 | 78.23 | 0.5047 | 20.85 | 0.25 | 342.92 |
| Voting | 288.44 | 0.8133 | 176.88 | 0.697 | 94.16 | 0.5423 | 27.71 | 0.2554 | 368.92 |
| Negotiation | 281.58 | 0.8129 | 183.7 | 0.7292 | 96.0 | 0.5775 | 24.34 | 0.25 | 366.36 |

Mbits/s), which would also correspond to the social welfare of the voting/negotiation if multiplied by the number of STAs.

A first but expected conclusion is that the farther STAs get the worse performance due to the propagation losses (which are especially pronounced in indoor environments). The second but important conclusion is that our proposals, although simple, outperform LCCS. Further, this improvement is independent of the distance between the AP and the STA.

The table also shows the Jain fairness index[16] for each distance interval. We see that there are no significant differences in fairness among the approaches for the STAs that are closest to the AP or for the STAs that are farthest. This is because, in these extreme cases, SINR is so high (or so low) due to the distance that channel selection does not make a difference. However, in the mid-ranges, which correspond to the majority of clients, we observe significant differences between LCCS and our proposals, where clients have an active role in the process.

## CONCLUSION AND DIRECTIONS

We propose shifting from the traditional network-centric approach to Wi-Fi network management to a more client-centric paradigms, where clients take an active role in channel assignment decision making. We show how this active client participation allows for fairer resource allocation. In addition, these new paradigms open the door to the use of collective intelligence and automated negotiation techniques, and end-user involvement in the process. There is, of course, no need for direct human involvement in the channel assignment procedure, since software agents installed in user devices can negotiate or vote on their behalf. However, an interesting direction is to request user input at different stages to better tailor the result to specific user needs and preferences.

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