APPENDIX A
PROOF OF SPECIAL-CASE TARGET ALLOCATION THEOREMS

When $\rho = 0$ and the QoE function takes Q_{lin} in Eq.1, optimizing the utility function is simplified into maximizing $\mathbb{U}' = \Sigma_i \min(d_i, \Sigma_{j\neq i} u_j)$, the average receiving bitrate of all clients.

A. Proof of the network-limited case

Thm.1 claims: If all clients have a half-duplex bottleneck, the bandwidth allocations to achieve the maximum utility (average receiving bitrate of all clients) are $\max^{2nd}(B_i) \leq \sum_i u_i \leq \max(B_i)$ and $d_i = B_i - u_i$.

Proof. Let $m_1 = argmax_i(B_i), m_2 = argmax_i(B_i, B_i < B_{m_1})$. When the condition in Thm. 1 is satisfied, the optimization objective $\mathbb{U}'_{opt} = \sum_{i\neq m_1} B_i$.

If $\sum_i d_i < \sum_{i\neq m_1} B_i$,

$$\mathbb{U}' = \sum_i d_i < \sum_{i\neq m_1} B_i = \mathbb{U}_{opt}$$

If $\sum_i d_i > \sum_{i\neq m_2} B_i$,

$$\begin{aligned}\mathbb{U}' &= \sum_{i\neq m_1} B_i - \sum_i d_i \\ &\quad + \sum_{i\neq m_1, m_2} \min(B_i, \sum_j B_j - \sum_j d_j) + B_{m_1} \\ &< \sum_{i\neq m_1} B_i - \sum_i d_i + \sum_{i\neq m_2} B_i < \mathbb{U}_{opt}\end{aligned}$$

Therefore, to achieve the maximum average bitrate, the following condition should be satisfied.

$$\sum_{i\neq m_1} B_i \leq \sum_i d_i \leq \sum_{i\neq m_2} B_i$$

Equivalently, $\max^{2nd}(B_i) \leq \sum_i u_i \leq \max(B_i)$ and the downlink should take up the rest of the capacity ($d_i = B_i - u_i$). □

B. Proof of the application-limited case

Thm.2 claims: If there exists at least one client with abundant network bandwidth (more than the sum of all flows under the maximum bitrate), then the uplink bandwidth of each client should be as large as possible to improve the utility (the average receiving bitrate of all clients).

Proof. We use the exchange argument in greedy algorithms [37] to prove this theorem. Assume that there are k application-limited users with abundant network bandwidth (the available bandwidth for these users exceeds $n\times$ the maximum application bitrate) and that the other users are network-limited. Assume an arbitrary bandwidth allocation. If we increase the uplink bandwidth of a network-limited user i by Δ, the downlink bandwidth of User i would decrease by Δ. However, the increased Δ uplink traffic would increase the bitrate of the k application-limited users by $k\Delta$ in total. Therefore, increasing the uplink bandwidth allocation would bring a destined profit to the average bitrate when $k > 1$, and would not decrease the average bitrate when $k = 1$. □

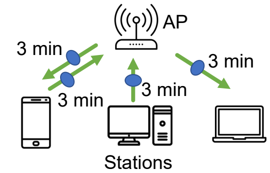

Figure 13: Per-flow fairness as a WiFi fairness notion in the history. The blue circles represent the basic unit of fairness. The 3 minutes are numerical examples of the fair airtime apportioned to each basic unit. The figure should be viewed in comparison with Fig.2.

APPENDIX B
THE EVOLUTION OF WIFI FAIRNESS NOTIONS

The fairness issue in WiFi has been broadly investigated. Based on the original MAC DCF, the AP competes for channel access as the other stations in one basic service set (BSS). When there are multiple downlink flows (to n stations), the downlink throughput to each station could only be $1/n$ of the uplink throughput. To cope with this unfairness, past research pursues *per-flow fairness* [55], [16], [49], [17], [71] by controlling the transmission opportunity (TXOP) limit or the minimum CW size or the channel sensing time (i.e., inter-frame space) at the AP. As shown in Fig.13, per-flow fairness attempts to provide a fair share of air interface bandwidth to each flow regardless of its direction or station. However, per-flow fairness could not provide fair resource sharing among stations, since some stations only have traffic flows in one direction. To ensure fairness from the viewpoint of each station, *per-station fairness* is proposed [56], [62] to provide fair resource apportioned to each station regardless of the direction of flows (Fig.2). Airtime fairness [38] merges this notion of per-station fairness and offers the same length of air time to each station to transfer its data regardless of the flow direction, which is now widely adopted by mainstream WiFi AP providers. Our design and experiments are based on the MAC access method with per-station fairness, so bidirectional bandwidth coordination would not impact other WLAN users.