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MANAGED MU-MIMO ENABLEMENT FOR REAL-WORLD APPLICATIONS

Abstract

This disclosure provides systems and methods for selectively enabling multi-user (MU) communications. In some implementations, an access point (AP) obtains one or more packets associated with a traffic flow, and obtains at least one of service-level agreement (SLA) parameters associated with the traffic flow, attributes of the traffic flow, or network parameters associated with a basic service set (BSS) that includes the AP. The AP provides an indication of whether the traffic flow is suitable for transmission as a single-user (SU) multiple-input multiple output (MIMO) (SU-MIMO) communication, as a multi-user (MU) MIMO (MU-MIMO) communication, as an orthogonal frequency division multiple access (OFDMA) communication, or as a partial bandwidth (BW) MU-MIMO communication to a WLAN subsystem of the AP, the indication being based on one or more of the SLA parameters, the traffic flow attributes, or the network parameters.

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Background/Summary

CROSS REFERENCE [0001] The present application for patent is a continuation of U.S. patent application Ser. No. 17/722,564 by ELSHERIF et al., entitled “MANAGED MU-MIMO ENABLEMENT FOR REAL-WORLD APPLICATIONS,” filed Apr. 18, 2022, assigned to the assignee hereof, and expressly incorporated by reference in its entirety herein.

TECHNICAL FIELD
[0002] This disclosure relates generally to wireless communication, and more specifically, to dynamically enabling multi-user (MU) communications for traffic flows transmitted over a wireless medium.
DESCRIPTION OF THE RELATED TECHNOLOGY
[0003] A wireless local area network (WLAN) may be formed by one or more access points (APs) that provide a shared wireless medium for use by a number of client devices such as wireless stations (STAs). The basic building block of a WLAN conforming to the Institute of Electrical and Electronics Engineers (IEEE) 802.11 family of standards is a Basic Service Set (BSS), which is managed by an AP. Each BSS is identified by a Basic Service Set Identifier (BSSID) that is advertised by the AP in beacon frames periodically broadcasted over the wireless medium so that STAs within wireless range of the AP can associate with the AP and establish a wireless communication link with the WLAN.
[0004] An AP may determine a transmission mode for each traffic flow that is communicated over the wireless medium. Example transmission modes may include single-user (SU) multiple-input multiple-output (MIMO) (SU-MIMO) transmissions, multi-user (MU) MIMO (MU-MIMO) transmissions, and orthogonal frequency division multiple access (OFDMA) communications. Some APs rely on feedback information from their respective wireless networks to determine the transmission modes for transmitting traffic flows over the wireless medium. The process by which an AP determines the transmission mode of a traffic flow based on feedback from its network may be referred to as a “control loop.” As wireless networks continue to grow, and wireless technologies continue to evolve, new mechanisms are needed to ensure that various control loops can converge on transmission mode decisions that are optimized for communications between wireless devices in the network.
SUMMARY
[0005] The following presents a simplified summary of one or more aspects in order to provide a basic understanding of such aspects. This summary is not an extensive overview of all contemplated aspects, and is intended to neither identify key or critical elements of all aspects nor delineate the scope of any or all aspects. Its sole purpose is to present some concepts of one or more aspects in a simplified form as a prelude to the more detailed description that is presented later.
[0006] One innovative aspect of the subject matter described in this disclosure can be implemented

as an apparatus for wireless communications. The apparatus may include at least a wireless local area network (WLAN) subsystem and a resource manager. The WLAN subsystem is configured to obtain one or more packets associated with a traffic flow. The resource manager is configured to obtain at least one of one or more service-level agreement (SLA) parameters of the traffic flow, one or more attributes of the traffic flow, or one or more network parameters associated with a basic service set (BSS) that includes the apparatus. The resource manager is also configured to provide an indication of whether the traffic flow is suitable for transmission over a wireless medium as a single-user (SU) multiple-input multiple output (MIMO) (SU-MIMO) communication, as a multi-user (MU) MIMO (MU-MIMO) communication, as an orthogonal frequency division multiple access (OFDMA) communication, or as a partial bandwidth (BW) MU-MIMO communication, the indication being based on one or more of the SLA parameters, the traffic flow attributes, or the network parameters. The WLAN subsystem is also configured to initiate transmission of the one or more packets over the wireless medium using a transmission mode based on the indication provided by the resource manager.

[0007] In various implementations, the resource manager may also be configured to assign a transmission mode to each packet queue associated with the traffic flow, the transmission mode being one of SU-MIMO, MU-MIMO, OFDMA, or partial BW MU-MIMO based on the indication. In some instances, the WLAN subsystem may also be configured to select the transmission mode for the one or more packets based on the indication. In some instances, the WLAN subsystem outputs for transmission the one or more packets as an MU-MIMO transmission based on the traffic flow being associated with latency-sensitive traffic and an amount of payload data carried by the one or more packets being at least equal to a threshold, or outputs for transmission the one or more packets as an OFDMA transmission based on the traffic flow being associated with latency-sensitive traffic and the amount of payload data carried by the one or more packets being less than the threshold. In other instances, the WLAN subsystem outputs for transmission the one or more packets as a partial BW MU-MIMO transmission based on the traffic flow being associated with latency-sensitive traffic and the number of active latency-sensitive traffic flows being at least equal to a threshold number of traffic flows, or outputs for transmission the one or more packets as an MU-MIMO transmission based on the traffic flow not being associated with latency-sensitive traffic and carrying more than a specified amount of data.

[0008] In some implementations, the SLA parameters may include one or more of a minimum data rate, a maximum delay bound, a service interval, a burst size, or a throughput requirement for traffic flows associated with the SLA. In some aspects, the WLAN subsystem outputs for transmission the one or more packets as an MU-MIMO transmission based at least in part on the maximum delay bound being at least equal to a delay threshold, the throughput requirement being at least equal to a throughput threshold, or both, or outputs for transmission the one or more packets as an OFDMA transmission based at least in part on the maximum delay bound being less than the delay threshold, the throughput requirement being less than the throughput threshold, or both. In some instances, the output for transmission as the MU-MIMO transmission may also be based on the minimum data rate being at least equal to a data rate threshold, and the output for transmission as the OFDMA transmission may also be based on the minimum data rate being less than the data rate threshold.

[0009] In various implementations, the network parameters may include one or more of interference levels on the wireless medium, a level of channel delay spread associated with the wireless medium, a number of associated wireless stations (STAs) that are active, a number or percentage of the active STAs that support MU-MIMO communications, a number or percentage of the active STAs that support partial BW MU-MIMO communications, a number or percentage of the active STAs that support OFDMA communications, one or more service class parameters, or a traffic load on the wireless medium. In some aspects, the WLAN subsystem outputs for transmission the one or more packets as an MU-MIMO transmission based at least in part on the interference levels being less than an interference threshold, the level of channel delay spread being less than a threshold amount, or both. In other aspects, the WLAN subsystem outputs for transmission the one or more packets as an OFDMA transmission based at least in part on the interference levels being at least equal to the interference threshold, the level of channel delay spread being at least equal to the threshold amount, or both. In some instances, the output for transmission as the MU-MIMO transmission may also be based on the number or percentage of active STAs that support MU-MIMO communications being at least equal to a first amount and the number of associated STAs being less than a second amount. In other instances, the output for transmission as the SU-MIMO or OFDMA transmission may also be based on the number or percentage of active STAs that support MU-MIMO communications being less than the first amount and the number of associated STAs being at least equal to the second amount.

[0010] In some implementations, the traffic flow attributes may include one or more of a data rate of the traffic flow, an average burst size of the traffic flow, or interarrival times of the one or more packets associated with the traffic flow. In some aspects, the WLAN subsystem outputs for transmission the one or more packets as an MU-MIMO transmission based on the respective interarrival times being offset in time from each other by less than a threshold time period and the average burst size being at least equal to a burst size threshold, or outputs for transmission the one or more packets as an SU-MIMO or OFDMA transmission based on the respective interarrival times being offset in time from each other by more than the threshold time period and the average burst size being less than the burst size threshold. In some instances, the output for transmission as the MU-MIMO transmission may also be based on the data rate being at least equal to a data rate threshold. In other instances, the output for transmission as the OFDMA transmission may also be based on the data rate being less than the data rate threshold.

[0011] In various aspects, the resource manager operates according to a first timing loop, and the WLAN subsystem operates according to a second timing loop, where the first timing loop is between approximately 1 and 100 milliseconds, and the second timing loop is between approximately 1 and 5 seconds. In some aspects, the resource manager is configured to obtain the network parameters and the traffic flow attributes based on a third timing loop, where the third timing loop is between approximately 10 and 60 seconds. In other aspects, the apparatus may also include a transceiver configured to transmit the one or more packets over the wireless medium. In some implementations, the apparatus may be configured as an access point (AP) associated with the BSS.

[0012] Another innovative aspect of the subject matter described in this disclosure can be implemented as a method for wireless communication at an access point (AP). The method may include obtaining one or more packets associated with a traffic flow, and obtaining at least one of one or more SLA parameters of the traffic flow, one or more attributes of the traffic flow, or one or more network parameters associated with a BSS that includes the AP. The method may include providing an indication of whether the traffic flow is suitable for transmission over a wireless medium as a single-user (SU) multiple-input multiple output (MIMO) (SU-MIMO) communication, as a multi-user (MU) MIMO (MU-MIMO) communication, as an orthogonal frequency division multiple access (OFDMA) communication, or as a partial BW MU-MIMO communication, the indication being based on one or more of the SLA parameters, the traffic flow attributes, or the network parameters. The method may include initiating transmission of the one or more packets over the wireless medium based on the indication.

[0013] In various implementations, the method may also include assigning a transmission mode to each packet queue associated with the traffic flow, the transmission mode being one of an SU-MIMO, MU-MIMO, OFDMA, or partial BW MU-MIMO based on the indication. In some aspects, the method may also include selecting a transmission mode for the WLAN subsystem based on the indication. In some instances, the method may also include outputting for transmission the one or more packets as an MU-MIMO transmission based on the traffic flow being associated with latency-sensitive traffic and an amount of payload data carried by the one or more packets being at least equal to a threshold, or outputting for transmission the one or more packets as an OFDMA transmission based on the traffic flow being associated with latency-sensitive traffic and the amount of payload data carried by the one or more packets being less than the threshold. In other instances, the WLAN subsystem outputs for transmission the one or more packets as a partial BW MU-MIMO transmission based on the traffic flow being associated with latency-sensitive traffic and the number of active latency-sensitive traffic flows being at least equal to a threshold number of traffic flows, or outputs for transmission the one or more packets as an MU-MIMO transmission based on the traffic flow not being associated with latency-sensitive traffic and carrying more than a specified amount of data.

[0014] In some implementations, the SLA parameters may include one or more of a minimum data rate, a maximum delay bound, a service interval, a burst size, or a throughput requirement for traffic flows associated with the SLA. In some aspects, the method may also include outputting for transmission the one or more packets as an MU-MIMO transmission based at least in part on the maximum delay bound being at least equal to a delay threshold, the throughput requirement being at least equal to a throughput threshold, or both, or outputting for transmission the one or more packets as an OFDMA transmission based at least in part on the maximum delay bound being less than the delay threshold, the throughput requirement being less than the throughput threshold, or both. In some instances, outputting the one or more packets for transmission as the MU-MIMO transmission may also be based on the minimum data rate being at least equal to a data rate threshold. In other instances, outputting the one or more packets for transmission as the OFDMA transmission may also be based on the minimum data rate being less than the data rate threshold.

[0015] In various implementations, the network parameters may include one or more of interference levels on the wireless medium, a level of channel delay spread associated with the wireless medium, a number of associated STAs that are active, a number or percentage of the active STAs that support MU-MIMO communications, a number or percentage of the active STAs that support partial BW MU-MIMO communications, a number or percentage of the active STAs that support OFDMA communications, one or more service class parameters, or a traffic load on the wireless medium. In some aspects, the method may also include outputting for transmission the one or more packets as an MU-MIMO transmission based at least in part on the interference levels being less than an interference threshold, the level of channel delay spread being less than a threshold amount, or both. In other aspects, the method may also include outputting for transmission the one or more packets as an OFDMA transmission based at least in part on the interference levels being at least equal to the interference threshold, the level of channel delay spread being at least equal to the threshold amount, or both. In some instances, outputting the one or more packets for transmission as the MU-MIMO transmission may also be based on the number or percentage of active STAs that support MU-MIMO communications being at least equal to a first amount and the number of active STAs being less than a second amount. In other instances, outputting the one or more packets for transmission as the SU-MIMO or OFDMA transmission may also be based on the number or percentage of active STAs that support MU-MIMO communications being less than the first amount and the number of active STAs being at least equal to the second amount.

[0016] In some implementations, the traffic flow attributes may include one or more of a data rate of the traffic flow, an average burst size of the traffic flow, or interarrival times of the one or more packets associated with the traffic flow. In some aspects, the method may also include outputting for transmission the one or more packets as the MU-MIMO transmission based on the respective interarrival times being offset in time from each other by less than a threshold time period and the average burst size being greater than a burst size threshold. In other aspects, the method may also include outputting for transmission the one or more packets as the SU-MIMO or OFDMA transmission based on the respective interarrival times being offset in time from each other by more than the threshold time period and the average burst size being less than the burst size threshold. In some instances, outputting the one or more packets for transmission as the MU-MIMO transmission may also be based on the data rate being at least equal to a data rate threshold. In other instances, outputting the one or more packets for transmission as the OFDMA transmission may also be based on the data rate being less than the data rate threshold.

[0017] In various aspects, obtaining the SLA parameters may be associated with a first timing loop, and providing the indication may be associated with a second timing loop, where the first timing loop is between approximately 1 and 100 milliseconds, and the second timing loop is between approximately 1 and 5 seconds. In some instances, obtaining the network parameters and the traffic flow attributes may be associated with a third timing loop, the third timing loop being between approximately 10 and 60 seconds.

[0018] Details of one or more implementations of the subject matter described in this disclosure are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages will become apparent from the description, the drawings and the claims. Note that the relative dimensions of the following figures may not be drawn to scale.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] FIG. **1** shows a pictorial diagram of an example wireless communication network.

[0020] FIG. **2**A shows an example protocol data unit (PDU) usable for communications between an access point (AP) and one or more wireless stations (STAs).

[0021] FIG. **2**B shows an example field in the PDU of FIG. **2**A.

[0022] FIG. **3**A shows another example PDU usable for communications between an AP and one or more STAs.

[0023] FIG. **3**B shows another example PDU usable for communications between an AP and one or more STAs.

[0024] FIG. **4** shows an example physical layer convergence protocol (PLCP) protocol data unit (PPDU) usable for communications between an AP and a number of STAs.

[0025] FIG. **5** shows a block diagram of an example wireless communication device.

[0026] FIG. **6**A shows a block diagram of an example access point (AP).

[0027] FIG. **6**B shows a block diagram of an example station (STA).

[0028] FIG. **7** shows a block diagram of another example wireless communication device.

[0029] FIG. **8** shows a block diagram of an example resource manager suitable for use in wireless communication devices disclosed herein.

[0030] FIG. **9**A shows a timing diagram depicting an example wireless communication that supports single-user (SU) multiple-input multiple output (MIMO) (SU-MIMO) communications.

[0031] FIG. **9**B shows a timing diagram depicting an example wireless communication that supports multi-user (MU) MIMO (MU-MIMO) communications.

[0032] FIG. **10** shows a timing diagram depicting an example wireless communication that supports grouping traffic flows for MU-MIMO communications, according to some implementations.

[0033] FIG. **11** shows a flowchart illustrating another example operation for wireless communication that supports selectively enabling MU-MIMO communications, according to some implementations.

[0034] FIG. **12** shows a flowchart illustrating an example operation for wireless communication that supports selectively enabling MU-MIMO communications, according to some implementations.

[0035] FIGS. **13**A-**13**E show flowcharts illustrating example operations for wireless communication that supports selectively enabling MU-MIMO communications, according to some implementations.

[0036] FIG. **14** shows a flowchart illustrating another example operation for wireless communication that supports grouping traffic flows for MU-MIMO communications, according to some implementations.

[0037] FIGS. **15**A-**15**D show flowcharts illustrating example operations for wireless communication that supports grouping traffic flows for MU-MIMO communications, according to some implementations.

[0038] FIGS. **16**A-**16**D show flowcharts illustrating example operations for wireless communication that supports selectively grouping traffic flows for MU-MIMO communications, according to some implementations.

[0039] FIG. **17** shows a conceptual data flow diagram illustrating the data flow between different means/components in an example apparatus.

[0040] FIG. **18** shows a diagram illustrating an example of a hardware implementation for an apparatus employing a processing system.

[0041] Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0042] The following description is directed to some particular implementations for the purposes of describing innovative aspects of this disclosure. However, a person having ordinary skill in the art will readily recognize that the teachings herein can be applied in a multitude of different ways. The described implementations can be implemented in any device, system or network that is capable of transmitting and receiving radio frequency (RF) signals according to one or more of the Long Term Evolution (LTE), 3G, 4G or 5G (New Radio (NR)) standards promulgated by the 3rd Generation Partnership Project (3GPP), the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards, the IEEE 802.15 standards, or the Bluetooth® standards as defined by the Bluetooth Special Interest Group (SIG), among others. The described implementations can be implemented in any device, system or network that is capable of transmitting and receiving RF signals according to one or more of the following technologies or techniques: code division multiple access (CDMA), time division multiple access (TDMA), frequency division multiple access (FDMA), orthogonal FDMA (OFDMA), single-carrier FDMA (SC-FDMA), single-user (SU) multiple-input multiple-output (MIMO) and multi-user (MU) MIMO. The described implementations also can be implemented using other wireless communication protocols or RF signals suitable for use in one or more of a wireless wide area network (WWAN), a wireless personal area network (WPAN), a wireless local area network (WLAN), or an internet of things (IoT) network.

[0043] As discussed, a “control loop” may refer to a process by which an AP selects or determines the transmission mode for transmitting traffic flows over a wireless network based on feedback obtained from the wireless network. In many APs, timing aspects of the control loop are based on decision or response times associated with their transceivers. For example, a transceiver may be configured to make decisions pertaining to just-in-time (JIT) scheduling and smart enhanced distributed channel access (EDCA) adjustments, among other examples, within a defined time period. This defined time period may be associated with a period or duration of the control loop, for example, such that the feedback may be obtained from the wireless network based on the decision times of the transceivers. However, selecting or determining the transmission mode of traffic flows communicated over a wireless network based on feedback associated with transceiver decision or response times may fail to consider various network parameters, traffic patterns, and other network metrics observed over longer periods of time.

[0044] Various aspects of the subject matter disclosed herein relate generally to transmission modes used for transmitting multiple traffic flows over a wireless medium, and more particularly, to selecting or adjusting the transmission modes based on feedback information obtained from one or more wireless networks, one or more attributes of the traffic flows, one or more service-level agreement (SLA) parameters of the traffic flows, or any combination thereof. In various implementations, an apparatus, such as an AP, may select single-user (SU) multiple-input multiple output (MIMO) (SU-MIMO), multi-user (MU) MIMO (MU-MIMO), orthogonal frequency division multiple access (OFDMA), or partial BW MU-MIMO as the transmission mode for transmitting one or more traffic flows over the wireless medium. In some instances, the apparatus may include a resource manager that provides an indication of whether a respective traffic flow is suitable for transmission over the wireless medium using SU-MIMO, MU-MIMO, OFDMA, or partial BW MU-MIMO communications. The apparatus may also include a wireless local area network (WLAN) subsystem configured to initiate the transmission of one or more traffic flows over the wireless medium based on the indication provided by the resource manager.

[0045] The indication may be based on one or more of the feedback information, the traffic flow attributes, or the SLA parameters. In some implementations, the feedback information may include network parameters, traffic patterns, and other information pertaining to one or more wireless networks (including the wireless network operated by the apparatus). In some instances, the network parameters may include one or more of interference levels on the wireless medium, a level of channel delay spread associated with the wireless medium, a number of associated wireless stations (STAs) that are active, a number or percentage of the active STAs that support MU-MIMO communications, a number or percentage of the active STAs that support partial BW MU-MIMO communications, a number or percentage of the active STAs that support OFDMA communications, one or more service class parameters, or a traffic load on the wireless medium. The SLA parameters may include one or more of a minimum data rate, a maximum delay bound, a service interval, a burst size, or a throughput requirement for traffic flows associated with the SLA. The traffic flow attributes may include at least a data rate of a respective traffic flow, an average burst size of the respective traffic flow, and interarrival times of packets associated with the respective traffic flow.

[0046] In some instances, the network parameters and the traffic flow attributes may be obtained based on a slow control loop having relatively slow decision times, and the transmission of traffic flows over the wireless medium may be based on a fast control loop having relatively fast decision times. In some aspects, the transmission mode indications provided by the resource manager may be based on a mid-control loop having decision times that are faster than the relatively slow decision times of the slow control loop, and that are slower than the relatively fast decision times of the fast control loop. In this way, aspects of the present disclosure may provide hierarchical levels of control for selecting or adjusting the transmission modes used for transmitting multiple traffic flows over the wireless medium in a manner that can increase network throughput and/or reduce network latencies (such as compared to conventional techniques based on a single control loop).

[0047] Aspects of the present disclosure recognize that MU-MIMO communications may achieve greater throughput and lower latencies than SU-MIMO communications by concurrently transmitting packets associated with multiple traffic flows to different users. Although OFDMA can also be used to concurrently transmit packets associated with multiple traffic flows to different users, OFDMA communications accommodate multiple users by allocating different frequency resources to each of the multiple traffic flows, thereby limiting each traffic flow of the multiple traffic flows to a corresponding portion of the bandwidth of the wireless network. In contrast to OFDMA communications, MU-MIMO communications accommodate multiple users by using spatial diversity techniques to distinguish between multiple traffic flows concurrently transmitted over the wireless medium, thereby allowing the transmission of each traffic flow of the multiple traffic flows to occupy the full bandwidth of the wireless network. As such, for at least some environments, MU-MIMO communications may achieve higher throughput and lower latencies than OFDMA communications.

[0048] Aspects of the present disclosure recognize that network throughput and latencies achieved by MU-MIMO communications may depend on a variety of factors including (but not limited to) interference levels on the wireless medium, channel delay spread associated with the wireless medium, the number of associated STAs that are active on the wireless medium, the number or percentage of active STAs that support MU-MIMO communications, channel correlation between multiple users, the amount of queued data for each traffic flow that is available for transmission, data rates of the traffic flows, burst sizes of the traffic flows, and burst periods of the traffic flows, among other examples. For example, any one or more of relatively high levels of channel correlation between a group of users, relatively high levels of interference, or relatively high levels of channel delay spread may decrease the ability of receiving devices to distinguish between the packets of different traffic flows concurrently transmitted over the wireless medium using MU-MIMO communications. As a result, MU-MIMO communications may not be suitable for transmitting multiple traffic flows over the wireless medium when one or more of these conditions are present. Therefore, in some implementations, the apparatus may disable MU-MIMO communications for transmitting multiple traffic flows over the wireless medium when one or more of the interference levels, channel correlations, or channel delay spread equals or exceeds one or more respective thresholds. In some instances, the apparatus may enable MU-MIMO communications for transmitting multiple traffic flows over the wireless medium when one or more of the interference levels, the channel correlations, or the channel delay spread is less than the one or more respective thresholds.

[0049] For another example, the apparatus may enable MU-MIMO communications for transmitting a group of traffic flows over the wireless medium when the number or percentage of active STAs that support MU-MIMO communications is relatively high (such as at least equal to a value), and may disable MU-MIMO communications for transmitting the traffic flows over the wireless medium when the number or percentage of active STAs that support MU-MIMO communications is relatively low (such as less than the value).

[0050] Aspects of the present disclosure also recognize that because the overhead of MU-MIMO communications is greater than the overhead of SU-MIMO communications (e.g., due to MU channel sounding, MU polling, and other frame exchanges associated with MU-MIMO communications), some traffic flows may not be suitable for transmission as an MU-MIMO communication unless the amount of queued downlink (DL) data of such the traffic flows is at least equal to a data threshold, for example, to compensate for the MU-MIMO overhead. As such, in some aspects, the apparatus may disable MU-MIMO communications for traffic flows having amounts of queued DL data that are less than the data threshold, and may enable MU-MIMO communications for traffic flows having amounts of queued DL data that equal or exceed the data threshold.

[0051] Particular implementations of the subject matter described in this disclosure can be implemented to realize one or more of the following potential advantages. By selecting the transmission modes used for transmitting multiple traffic flows over a wireless medium based on network parameters of one or more wireless networks, one or more traffic flow attributes, or one or more SLA parameters of the traffic flows, an apparatus configured according to various aspects of the present disclosure may concurrently transmit multiple traffic flows over the wireless medium based on a selection of one of SU-MIMO communications, MU-MIMO communications, OFDMA communications, or partial BW MU-MIMO communications that that maximizes network throughput and minimizes network latencies. In addition, the ability to dynamically adjust the transmission mode used for transmitting a respective traffic flow over the wireless medium based on one or more of the network parameters, the traffic flow attributes, or the respective SLA parameters may allow the apparatus to maintain network throughput and latencies when one or more network conditions change. Also, by using a hierarchical control loop to not only obtain network parameters and traffic flow attributes of one or more wireless networks, but also to make transmission mode decisions based at least in part on network parameters and traffic flow attributes observed over relatively long periods of time (e.g., as compared to the relatively short periods of

time associated with decision and response times of PHY devices), which may increase the accuracy with which the apparatus determines the most suitable transmission for a particular traffic flow.
[0052] FIG. **1** shows a block diagram of an example wireless communication network **100**. According to some aspects, the wireless communication network **100** can be an example of a wireless local area network (WLAN) such as a Wi-Fi network (and will hereinafter be referred to as WLAN **100**). For example, the WLAN **100** can be a network implementing at least one of the IEEE 802.11 family of standards (such as that defined by the IEEE 802.11-2016 specification or amendments thereof including, but not limited to, 802.11ah, 802.11ad, 802.11ay, 802.11ax, 802.11az, 802.11ba, and 802.11be). The WLAN **100** may include numerous wireless communication devices such as an access point (AP) **102** and multiple stations (STAs) **104**. While only one AP **102** is shown, the WLAN **100** also can include multiple APs **102**.
[0053] Each of the STAs **104** also may be referred to as a mobile station (MS), a mobile device, a mobile handset, a wireless handset, an access terminal (AT), a user equipment (UE), a subscriber station (SS), or a subscriber unit, among other possibilities. The STAs **104** may represent various devices such as mobile phones, personal digital assistant (PDAs), other handheld devices, netbooks, notebook computers, tablet computers, laptops, display devices (for example, TVs, computer monitors, navigation systems, among others), music or other audio or stereo devices, remote control devices (“remotes”), printers, kitchen or other household appliances, key fobs (for example, for passive keyless entry and start (PKES) systems), among other possibilities.
[0054] A single AP **102** and an associated set of STAs **104** may be referred to as a basic service set (BSS), which is managed by the respective AP **102**. FIG. **1** additionally shows an example coverage area **106** of the AP **102**, which may represent a basic service area (BSA) of the WLAN **100**. The BSS may be identified to users by a service set identifier (SSID), as well as to other devices by a basic service set identifier (BSSID), which may be a medium access control (MAC) address of the AP **102**. The AP **102** periodically broadcasts beacon frames (“beacons”) including the BSSID to enable any STAs **104** within wireless range of the AP **102** to “associate” or re-associate with the AP **102** to establish a respective communication link **108** (hereinafter also referred to as a “Wi-Fi link”), or to maintain a communication link **108**, with the AP **102**. For example, the beacons can include an identification of a primary channel used by the respective AP **102** as well as a timing synchronization function for establishing or maintaining timing synchronization with the AP **102**. The AP **102** may provide access to external networks to various STAs **104** in the WLAN via respective communication links **108**.
[0055] To establish a communication link **108** with an AP **102**, each of the STAs **104** is configured to perform passive or active scanning operations (“scans”) on frequency channels in one or more frequency bands (for example, the 2.4 GHz, 5.0 GHZ, 6.0 GHZ, or 60 GHz bands). To perform passive scanning, a STA **104** listens for beacons, which are transmitted by respective APs **102** at a periodic time interval referred to as the target beacon transmission time (TBTT) (measured in time units (TUs) where one TU may be equal to 1024 microseconds (μs)). To perform active scanning, a STA **104** generates and sequentially transmits probe requests on each channel to be scanned and listens for probe responses from APs **102**. Each STA **104** may be configured to identify or select an AP **102** with which to associate based on the scanning information obtained through the passive or active scans, and to perform authentication and association operations to establish a communication link **108** with the selected AP **102**. The AP **102** assigns an association identifier (AID) to the STA **104** at the culmination of the association operations, which the AP **102** uses to track the STA **104**.
[0056] As a result of the increasing ubiquity of wireless networks, a STA **104** may have the opportunity to select one of many BSSs within range of the STA or to select among multiple APs **102** that together form an extended service set (ESS) including multiple connected BSSs. An extended network station associated with the WLAN **100** may be connected to a wired or wireless distribution system that may allow multiple APs **102** to be connected in such an ESS. As such, a

STA **104** can be covered by more than one AP **102** and can associate with different APs **102** at different times for different transmissions. Additionally, after association with an AP **102**, a STA **104** also may be configured to periodically scan its surroundings to find a more suitable AP **102** with which to associate. For example, a STA **104** that is moving relative to its associated AP **102** may perform a "roaming" scan to find another AP **102** having more desirable network characteristics such as a greater received signal strength indicator (RSSI) or a reduced traffic load.

[0057] In some cases, STAs **104** may form networks without APs **102** or other equipment other than the STAs **104** themselves. One example of such a network is an ad hoc network (or wireless ad hoc network). Ad hoc networks may alternatively be referred to as mesh networks or peer-to-peer (P2P) networks. In some cases, ad hoc networks may be implemented within a larger wireless network such as the WLAN **100**. In such implementations, while the STAs **104** may be capable of communicating with each other through the AP **102** using communication links **108**, STAs **104** also can communicate directly with each other via direct communication links **110**. Additionally, two STAs **104** may communicate via a direct communication link **110** regardless of whether both STAs **104** are associated with and served by the same AP **102**. In such an ad hoc system, one or more of the STAs **104** may assume the role filled by the AP **102** in a BSS. Such a STA **104** may be referred to as a group owner (GO) and may coordinate transmissions within the ad hoc network. Examples of direct communication links **110** include Wi-Fi Direct connections, connections established by using a Wi-Fi Tunneled Direct Link Setup (TDLS) link, and other P2P group connections.

[0058] The APs **102** and STAs **104** may function and communicate (via the respective communication links **108**) according to the IEEE 802.11 family of standards (such as that defined by the IEEE 802.11-2016 specification or amendments thereof including, but not limited to, 802.11ah, 802.11ad, 802.11ay, 802.11ax, 802.11az, 802.11ba, and 802.11be). These standards define the WLAN radio and baseband protocols for the PHY and medium access control (MAC) layers. The APs **102** and STAs **104** transmit and receive wireless communications (hereinafter also referred to as "Wi-Fi communications") to and from one another in the form of physical layer convergence protocol (PLCP) protocol data units (PPDUs). The APs **102** and STAs **104** in the WLAN **100** may transmit PPDUs over an unlicensed spectrum, which may be a portion of spectrum that includes frequency bands traditionally used by Wi-Fi technology, such as the 2.4 GHz band, the 5.0 GHz band, the 60 GHz band, the 3.6 GHz band, and the 900 MHz band. Some implementations of the APs **102** and STAs **104** described herein also may communicate in other frequency bands, such as the 6.0 GHz band, which may support both licensed and unlicensed communications. The APs **102** and STAs **104** also can be configured to communicate over other frequency bands such as shared licensed frequency bands, where multiple operators may have a license to operate in the same or overlapping frequency band or bands.

[0059] Each of the frequency bands may include multiple sub-bands or frequency channels. For example, PPDUs conforming to the IEEE 802.11n, 802.11ac, and 802.11ax standard amendments may be transmitted over the 2.4 and 5.0 GHz bands, each of which is divided into multiple 20 MHz channels. As such, these PPDUs are transmitted over a physical channel having a minimum bandwidth of 20 MHz, but larger channels can be formed through channel bonding. For example, PPDUs may be transmitted over physical channels having bandwidths of 40 MHz, 80 MHz, 160, or 320 MHz by bonding together multiple 20 MHz channels.

[0060] Each PPDU is a composite structure that includes a PHY preamble and a payload in the form of a PLCP service data unit (PSDU). The information provided in the preamble may be used by a receiving device to decode the subsequent data in the PSDU. In instances in which PPDUs are transmitted over a bonded channel, the preamble fields may be duplicated and transmitted in each of the multiple component channels. The PHY preamble may include both a legacy portion (or "legacy preamble") and a non-legacy portion (or "non-legacy preamble"). The legacy preamble may be used for packet detection, automatic gain control and channel estimation, among other uses. The legacy preamble also may generally be used to maintain compatibility with legacy devices.

The format of, coding of, and information provided in the non-legacy portion of the preamble is based on the particular IEEE 802.11 protocol to be used to transmit the payload.

[0061] FIG. **2**A shows an example protocol data unit (PDU) **200** usable for wireless communication between an AP **102** and one or more STAs **104**. For example, the PDU **200** can be configured as a PPDU. As shown, the PDU **200** includes a PHY preamble **202** and a payload **204**. For example, the preamble **202** may include a legacy portion that itself includes a legacy short training field (L-STF) **206**, which may consist of two BPSK symbols, a legacy long training field (L-LTF) **208**, which may consist of two BPSK symbols, and a legacy signal field (L-SIG) **210**, which may consist of two BPSK symbols. The legacy portion of the preamble **202** may be configured according to the IEEE 802.11a wireless communication protocol standard. The preamble **202** also may include a non-legacy portion including one or more non-legacy fields **212**, for example, conforming to an IEEE wireless communication protocol such as the IEEE 802.11ac, 802.11ax, 802.11be or later wireless communication protocol protocols.

[0062] The L-STF **206** generally enables a receiving device to perform automatic gain control (AGC) and coarse timing and frequency estimation. The L-LTF **208** generally enables a receiving device to perform fine timing and frequency estimation and also to perform an initial estimate of the wireless channel. The L-SIG **210** generally enables a receiving device to determine a duration of the PDU and to use the determined duration to avoid transmitting on top of the PDU. For example, the L-STF **206**, the L-LTF **208** and the L-SIG **210** may be modulated according to a binary phase shift keying (BPSK) modulation scheme. The payload **204** may be modulated according to a BPSK modulation scheme, a quadrature BPSK (Q-BPSK) modulation scheme, a quadrature amplitude modulation (QAM) modulation scheme, or another appropriate modulation scheme. The payload **204** may include a PSDU including a data field (DATA) **214** that, in turn, may carry higher layer data, for example, in the form of medium access control (MAC) protocol data units (MPDUs) or an aggregated MPDU (A-MPDU).

[0063] FIG. **2**B shows an example L-SIG **210** in the PDU **200** of FIG. **2**A. The L-SIG **210** includes a data rate field **222**, a reserved bit **224**, a length field **226**, a parity bit **228**, and a tail field **230**. The data rate field **222** indicates a data rate (note that the data rate indicated in the data rate field **222** may not be the actual data rate of the data carried in the payload **204**). The length field **226** indicates a length of the packet in units of, for example, symbols or bytes. The parity bit **228** may be used to detect bit errors. The tail field **230** includes tail bits that may be used by the receiving device to terminate operation of a decoder (for example, a Viterbi decoder). The receiving device may utilize the data rate and the length indicated in the data rate field **222** and the length field **226** to determine a duration of the packet in units of, for example, microseconds (μs) or other time units.

[0064] FIG. **3**A shows another example PDU **300** usable for wireless communication between an AP and one or more STAs. The PDU **300** may be used for SU, OFDMA or MU-MIMO transmissions. The PDU **300** may be formatted as a High Efficiency (HE) WLAN PPDU in accordance with the IEEE 802.11ax amendment to the IEEE 802.11 wireless communication protocol standard. The PDU **300** includes a PHY preamble including a legacy portion **302** and a non-legacy portion **304**. The PDU **300** may further include a payload **306** after the preamble, for example, in the form of a PSDU including a data field **324**.

[0065] The legacy portion **302** of the preamble includes an L-STF **308**, an L-LTF **310**, and an L-SIG **312**. The non-legacy portion **304** includes a repetition of L-SIG (RL-SIG) **314**, a first HE signal field (HE-SIG-A) **316**, an HE short training field (HE-STF) **320**, and one or more HE long training fields (or symbols) (HE-LTFs) **322**. For OFDMA or MU-MIMO communications, the non-legacy portion **304** further includes a second HE signal field (HE-SIG-B) **318** encoded separately from HE-SIG-A **316**. Like the L-STF **308**, L-LTF **310**, and L-SIG **312**, the information in RL-SIG **314** and HE-SIG-A **316** may be duplicated and transmitted in each of the component 20 MHz channels in instances involving the use of a bonded channel. In contrast, the content in HE-SIG-B

318 may be unique to each 20 MHz channel and target specific STAs **104**.

[0066] RL-SIG **314** may indicate to HE-compatible STAs **104** that the PDU **300** is an HE PPDU. An AP **102** may use HE-SIG-A **316** to identify and inform multiple STAs **104** that the AP has scheduled UL or DL resources for them. For example, HE-SIG-A **316** may include a resource allocation subfield that indicates resource allocations for the identified STAs **104**. HE-SIG-A **316** may be decoded by each HE-compatible STA **104** served by the AP **102**. For MU transmissions, HE-SIG-A **316** further includes information usable by each identified STA **104** to decode an associated HE-SIG-B **318**. For example, HE-SIG-A **316** may indicate the frame format, including locations and lengths of HE-SIG-B **318**, available channel bandwidths and modulation and coding schemes (MCSs), among other examples. HE-SIG-A **316** also may include HE WLAN signaling information usable by STAs **104** other than the identified STAs **104**.

[0067] HE-SIG-B **318** may carry STA-specific scheduling information such as, for example, STA-specific (or “user-specific”) MCS values and STA-specific RU allocation information. In the context of DL transmissions, such information enables the respective STAs **104** to identify and decode corresponding resource units (RUs) in the associated data field **324**. Each HE-SIG-B **318** includes a common field and at least one STA-specific field. The common field can indicate RU allocations to multiple STAs **104** including RU assignments in the frequency domain, indicate which RUs are allocated for MU-MIMO transmissions and which RUs correspond to partial BW MU-MIMO transmissions, and the number of users in allocations, among other examples. The common field may be encoded with common bits, CRC bits, and tail bits. The user-specific fields are assigned to particular STAs **104** and may be used to schedule specific RUs and to indicate the scheduling to other WLAN devices. Each user-specific field may include multiple user block fields. Each user block field may include two user fields that contain information for two respective STAs to decode their respective RU payloads in data field **324**.

[0068] FIG. **3**B shows another example PPDU **350** usable for wireless communication between an AP and one or more STAs. The PDU **350** may be used for SU, OFDMA or MU-MIMO transmissions. The PDU **350** may be formatted as an Extreme High Throughput (EHT) WLAN PPDU in accordance with the IEEE 802.11be amendment to the IEEE 802.11 wireless communication protocol standard, or may be formatted as a PPDU conforming to any later (post-EHT) version of a new wireless communication protocol conforming to a future IEEE 802.11 wireless communication protocol standard or other wireless communication standard. The PDU **350** includes a PHY preamble including a legacy portion **352** and a non-legacy portion **354**. The PDU **350** may further include a PHY payload **356** after the preamble, for example, in the form of a PSDU including a data field **376**.

[0069] The legacy portion **352** of the preamble includes an L-STF **358**, an L-LTF **360**, and an L-SIG **362**. The non-legacy portion **354** of the preamble includes an RL-SIG **364** and multiple wireless communication protocol version-dependent signal fields after RL-SIG **364**. For example, the non-legacy portion **354** may include a universal signal field **366** (referred to herein as “U-SIG **366**”) and an EHT signal field **368** (referred to herein as “EHT-SIG **368**”). One or both of U-SIG **366** and EHT-SIG **368** may be structured as, and carry version-dependent information for, other wireless communication protocol versions beyond EHT. The non-legacy portion **354** further includes an additional short training field **372** (referred to herein as “EHT-STF **372**,” although it may be structured as, and carry version-dependent information for, other wireless communication protocol versions beyond EHT) and one or more additional long training fields **374** (referred to herein as “EHT-LTFs **374**,” although they may be structured as, and carry version-dependent information for, other wireless communication protocol versions beyond EHT). Like L-STF **358**, L-LTF **360**, and L-SIG **362**, the information in U-SIG **366** and EHT-SIG **368** may be duplicated and transmitted in each of the component 20 MHz channels in instances involving the use of a bonded channel. In some implementations, EHT-SIG **368** may additionally or alternatively carry information in one or more non-primary 20 MHz channels that is different than the information carried in the primary 20 MHz channel.

[0070] EHT-SIG **368** may include one or more jointly encoded symbols and may be encoded in a different block from the block in which U-SIG **366** is encoded. EHT-SIG **368** may be used by an AP to identify and inform multiple STAs **104** that the AP has scheduled UL or DL resources for them. EHT-SIG **368** may be decoded by each compatible STA **104** served by the AP **102**. EHT-SIG **368** may be used by a receiving device to interpret bits in the data field **376**. For example, EHT-SIG **368** may include RU allocation information, spatial stream configuration information, and per-user signaling information such as MCSs, among other examples. EHT-SIG **368** may further include a cyclic redundancy check (CRC) (for example, four bits) and a tail (for example, 6 bits) that may be used for binary convolutional code (BCC). In some implementations, EHT-SIG **368** may include one or more code blocks that each include a CRC and a tail. In some aspects, each of the code blocks may be encoded separately.

[0071] EHT-SIG **368** may carry STA-specific scheduling information such as, for example, user-specific MCS values and user-specific RU allocation information. EHT-SIG **368** may be used by a receiving device to interpret bits in the data field **376**. In the context of DL transmissions, such information enables the respective STAs **104** to identify and decode corresponding RUs in the associated data field **376**. Each EHT-SIG **368** may include a common field and at least one user-specific field. The common field can indicate RU distributions to multiple STAs **104**, indicate the RU assignments in the frequency domain, indicate which RUs are allocated for MU-MIMO transmissions and which RUs correspond to partial BW MU-MIMO transmissions, and the number of users in allocations, among other examples. The common field may be encoded with common bits, CRC bits, and tail bits. The user-specific fields are assigned to particular STAs **104** and may be used to schedule specific RUs and to indicate the scheduling to other WLAN devices. Each user-specific field may include multiple user block fields. Each user block field may include, for example, two user fields that contain information for two respective STAs to decode their respective RU payloads.

[0072] The presence of RL-SIG **364** and U-SIG **366** may indicate to EHT- or later version-compliant STAs **104** that the PPDU **350** is an EHT PPDU or a PPDU conforming to any later (post-EHT) version of a new wireless communication protocol conforming to a future IEEE 802.11 wireless communication protocol standard. For example, U-SIG **366** may be used by a receiving device to interpret bits in one or more of EHT-SIG **368** or the data field **376**.

[0073] FIG. **4** shows an example PPDU **400** usable for communications between an AP **102** and a number of STAs **104**. As described above, each PPDU **400** includes a PHY preamble **402** and a PSDU **404**. Each PSDU **404** may carry one or more MAC protocol data units (MPDUs), for example, such as an aggregated MPDU (A-MPDU) **406** that includes multiple MPDU subframes **408**. Each MPDU subframe **408** may include a MAC delimiter **412** and a MAC header **414** prior to the accompanying frame body **416**, which includes the data portion or "payload" of the MPDU subframe **408**. The frame body **416** may carry one or more MAC service data units (MSDUs), for example, such as an aggregated MSDU (A-MSDU) **422** that includes multiple MSDU subframes **424**. Each MSDU subframe **424** contains a corresponding MSDU **426** including a subframe header **428**, a frame body **430**, and one or more padding bits **432**.

[0074] Referring back to the A-MPDU subframe **406**, the MAC header **414** may include a number of fields containing information that defines or indicates characteristics or attributes of data encapsulated within the frame body **416**. The MAC header **414** also includes a number of fields indicating addresses for the data encapsulated within the frame body **416**. For example, the MAC header **414** may include a combination of a source address, a transmitter address, a receiver address, or a destination address. The MAC header **414** may include a frame control field containing control information. The frame control field specifies the frame type, for example, a data frame, a control frame, or a management frame. The MAC header **414** may further include a duration field indicating a duration extending from the end of the PPDU until the end of an

acknowledgment (ACK) of the last PPDU to be transmitted by the wireless communication device (for example, a block ACK (BA) in the case of an A-MPDU). The use of the duration field serves to reserve the wireless medium for the indicated duration, thus establishing the NAV. Each A-MPDU subframe **408** may also include a frame check sequence (FCS) field **418** for error detection. For example, the FCS field **418** may include a cyclic redundancy check (CRC), and may be followed by one or more padding bits **420**.
[0075] As described above, APs **102** and STAs **104** can support multi-user (MU) communications. That is, concurrent transmissions from one device to each of multiple devices (for example, multiple simultaneous downlink (DL) communications from an AP **102** to corresponding STAs **104**), or concurrent transmissions from multiple devices to a single device (for example, multiple simultaneous uplink (UL) transmissions from corresponding STAs **104** to an AP **102**). To support the MU transmissions, the APs **102** and STAs **104** may utilize multi-user multiple-input, multiple-output (MU-MIMO) and partial bandwidth (BW) MU-MIMO techniques.
[0076] In partial BW MU-MIMO schemes, the available frequency spectrum of the wireless channel may be divided into multiple resource units (RUs) each including a number of different frequency subcarriers ("tones"). Different RUs may be allocated or assigned by an AP **102** to different STAs **104** at particular times. The sizes and distributions of the RUs may be referred to as an RU allocation. In some implementations, RUs may be allocated in 2 MHz intervals, and as such, the smallest RU may include 26 tones consisting of 24 data tones and 2 pilot tones. Consequently, in a 20 MHz channel, up to 9 RUs (such as 2 MHz, 26-tone RUs) may be allocated (because some tones are reserved for other purposes). Similarly, in a 160 MHz channel, up to 74 RUs may be allocated. Larger 52 tone, 106 tone, 242 tone, 484 tone and 996 tone RUs may also be allocated. Adjacent RUs may be separated by a null subcarrier (such as a DC subcarrier), for example, to reduce interference between adjacent RUs, to reduce receiver DC offset, and to avoid transmit center frequency leakage.
[0077] For UL MU transmissions, an AP **102** can transmit a trigger frame to initiate and synchronize an UL partial BW MU-MIMO or UL MU-MIMO transmission from multiple STAs **104** to the AP **102**. Such trigger frames may thus enable multiple STAs **104** to send UL traffic to the AP **102** concurrently in time. A trigger frame may address one or more STAs **104** through respective association identifiers (AIDs), and may assign each AID (and thus each STA **104**) one or more RUs that can be used to send UL traffic to the AP **102**. The AP also may designate one or more random access (RA) RUs that unscheduled STAs **104** may contend for.
[0078] FIG. **5** shows a block diagram of an example wireless communication device **500**. In some implementations, the wireless communication device **500** can be an example of a device for use in a STA such as one of the STAs **104** described above with reference to FIG. **1**. In some implementations, the wireless communication device **500** can be an example of a device for use in an AP such as the AP **102** described above with reference to FIG. **1**. The wireless communication device **500** is capable of transmitting (or outputting for transmission) and receiving wireless communications (for example, in the form of wireless packets). For example, the wireless communication device **500** can be configured to transmit and receive packets in the form of physical layer convergence protocol (PLCP) protocol data units (PPDUs) and medium access control (MAC) protocol data units (MPDUs) conforming to an IEEE 802.11 standard, such as that defined by the IEEE 802.11-2016 specification or amendments thereof including, but not limited to, 802.11ah, 802.11ad, 802.11ay, 802.11ax, 802.11az, 802.11ba, and 802.11be.
[0079] The wireless communication device **500** can be, or can include, a chip, system on chip (SoC), chipset, package, or device that includes one or more modems **502**, for example, a Wi-Fi (IEEE 802.11 compliant) modem. In some implementations, the one or more modems **502** (collectively "the modem **502**") additionally include a WWAN modem (for example, a 3GPP 4G LTE or 5G compliant modem). In some implementations, the wireless communication device **500** also includes one or more radios **504** (collectively "the radio **504**"). In some implementations, the

wireless communication device **500** further includes one or more processors, processing blocks or processing elements (collectively "the processor **506**"), and one or more memory blocks or elements (collectively "the memory **508**").

[0080] The modem **502** can include an intelligent hardware block or device such as, for example, an application-specific integrated circuit (ASIC) among other possibilities. The modem **502** is configured to implement a PHY layer. For example, the modem **502** is configured to modulate packets and to output the modulated packets to the radio **504** for transmission over the wireless medium. The modem **502** is similarly configured to obtain modulated packets received by the radio **504** and to demodulate the packets to provide demodulated packets. In addition to a modulator and a demodulator, the modem **502** may further include digital signal processing (DSP) circuitry, automatic gain control (AGC), a coder, a decoder, a multiplexer, and a demultiplexer. For example, while in a transmission mode, data obtained from the processor **506** is provided to a coder, which encodes the data to provide encoded bits. The encoded bits are then mapped to points in a modulation constellation (using a selected MCS) to provide modulated symbols. The modulated symbols may then be mapped to a number N.sub.SS of spatial streams or a number N.sub.STS of space-time streams. The modulated symbols in the respective spatial or space-time streams may then be multiplexed, transformed via an inverse fast Fourier transform (IFFT) block, and subsequently provided to the DSP circuitry for Tx windowing and filtering. The digital signals may then be provided to a digital-to-analog converter (DAC). The resultant analog signals may then be provided to a frequency upconverter, and, the radio **504**. In implementations involving beamforming, the modulated symbols in the respective spatial streams are precoded via a steering matrix prior to their provision to the IFFT block.

[0081] While in a reception mode, digital signals received from the radio **504** are provided to the DSP circuitry, which is configured to acquire a received signal, for example, by detecting the presence of the signal and estimating the initial timing and frequency offsets. The DSP circuitry is further configured to digitally condition the digital signals, for example, using channel (narrowband) filtering, analog impairment conditioning (such as correcting for I/Q imbalance), and applying digital gain to obtain a narrowband signal. The output of the DSP circuitry may then be fed to the AGC, which is configured to use information extracted from the digital signals, for example, in one or more received training fields, to determine an appropriate gain. The output of the DSP circuitry also is coupled with the demodulator, which is configured to extract modulated symbols from the signal and, for example, compute the logarithm likelihood ratios (LLRs) for each bit position of each subcarrier in each spatial stream. The demodulator is coupled with the decoder, which may be configured to process the LLRs to provide decoded bits. The decoded bits from all of the spatial streams are then fed to the demultiplexer for demultiplexing. The demultiplexed bits may then be descrambled and provided to the MAC layer (the processor **506**) for processing, evaluation, or interpretation.

[0082] The radio **504** includes at least one radio frequency (RF) transmitter (or "transmitter chain") and at least one RF receiver (or "receiver chain"), which may be combined into one or more transceivers. For example, the RF transmitters and receivers may include various DSP circuitry including at least one power amplifier (PA) and at least one low-noise amplifier (LNA), respectively. The RF transmitters and receivers may in turn be coupled to one or more antennas. For example, in some implementations, the wireless communication device **500** can include, or be coupled with, multiple transmit antennas (each with a corresponding transmit chain) and multiple receive antennas (each with a corresponding receive chain). The symbols output from the modem **502** are provided to the radio **504**, which then transmits the symbols via the coupled antennas. Similarly, symbols received via the antennas are obtained by the radio **504**, which then provides the symbols to the modem **502**.

[0083] The processor **506** can include an intelligent hardware block or device such as, for example, a processing core, a processing block, a central processing unit (CPU), a microprocessor, a microcontroller, a digital signal processor (DSP), an application-specific integrated circuit (ASIC), a programmable logic device (PLD) such as a field programmable gate array (FPGA), discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. The processor **506** processes information received through the radio **504** and the modem **502**, and processes information to be output through the modem **502** and the radio **504** for transmission through the wireless medium. For example, the processor **506** may implement a control plane and MAC layer configured to perform various operations related to the generation and transmission of MPDUs, frames, or packets. The MAC layer is configured to perform or facilitate the coding and decoding of frames, spatial multiplexing, space-time block coding (STBC), beamforming, and OFDMA resource allocation, among other operations or techniques. In some implementations, the processor **506** may control the modem **502** to cause the modem to perform various operations described above.

[0084] The memory **508** can include tangible storage media such as random-access memory (RAM) or read-only memory (ROM), or combinations thereof. The memory **508** also can store non-transitory processor- or computer-executable software (SW) code containing instructions that, when executed by the processor **506**, cause the processor to perform various operations described herein for wireless communication, including the generation, transmission, reception, and interpretation of MPDUs, frames or packets. For example, various functions of components disclosed herein, or various blocks or steps of a method, operation, process, or algorithm disclosed herein, can be implemented as one or more modules of one or more computer programs.

[0085] FIG. **6**A shows a block diagram of an example AP **602**. For example, the AP **602** can be an example implementation of the AP **102** described with reference to FIG. **1**. The AP **602** includes a wireless communication device (WCD) **610**. For example, the wireless communication device **610** may be an example implementation of the wireless communication device **500** described with reference to FIG. **5**. The AP **602** also includes multiple antennas **620** coupled with the wireless communication device **610** to transmit and receive wireless communications. In some implementations, the AP **602** additionally includes an application processor **630** coupled with the wireless communication device **610**, and a memory **640** coupled with the application processor **630**. The AP **602** further includes at least one external network interface **650** that enables the AP **602** to communicate with a core network or backhaul network to gain access to external networks including the Internet. For example, the external network interface **650** may include one or both of a wired (for example, Ethernet) network interface and a wireless network interface (such as a WWAN interface). Ones of the aforementioned components can communicate with other ones of the components directly or indirectly, over at least one bus. The AP **602** further includes a housing that encompasses the wireless communication device **610**, the application processor **630**, the memory **640**, and at least portions of the antennas **620** and external network interface **650**.

[0086] FIG. **6**B shows a block diagram of an example STA **604**. For example, the STA **604** can be an example implementation of the STA **104** described with reference to FIG. **1**. The STA **604** includes a wireless communication device **615**. For example, the wireless communication device **615** may be an example implementation of the wireless communication device **500** described with reference to FIG. **5**. The STA **604** also includes one or more antennas **625** coupled with the wireless communication device **615** to transmit and receive wireless communications. The STA **604** additionally includes an application processor **635** coupled with the wireless communication device **615**, and a memory **645** coupled with the application processor **635**. In some implementations, the STA **604** further includes a user interface (UI) **655** (such as a touchscreen or keypad) and a display **665**, which may be integrated with the UI **655** to form a touchscreen display. In some implementations, the STA **604** may further include one or more sensors **675** such as, for example, one or more inertial sensors, accelerometers, temperature sensors, pressure sensors, or altitude sensors. Ones of the aforementioned components can communicate with other ones of the components directly or indirectly, over at least one bus. The STA **604** further includes a housing that encompasses the wireless communication device **615**, the application processor **635**, the memory **645**, and at least portions of the antennas **625**, UI **655**, and display **665**.

[0087] As discussed, various aspects of the subject matter disclosed herein relate generally to transmission modes used for transmitting multiple traffic flows over a wireless medium, and more particularly, to selecting or adjusting the transmission modes based on feedback information obtained from one or more wireless networks, one or more attributes of the traffic flows, one or more SLA parameters of the traffic flows, or any combination thereof. In some implementations, the feedback information may include network parameters, traffic patterns, and other information pertaining to one or more wireless networks (including the wireless network operated by the apparatus). In some instances, the network parameters may include one or more of interference levels on the wireless medium, a level of channel delay spread associated with the wireless medium, a number of associated wireless stations (STAs) that are active, a number or percentage of the active STAs that support MU-MIMO communications, a number or percentage of the active STAs that support partial BW MU-MIMO communications, a number or percentage of the active STAs that support OFDMA communications, one or more service class parameters, or a traffic load on the wireless medium. The SLA parameters may include one or more of a minimum data rate, a maximum delay bound, a service interval, a burst size, or a throughput requirement for traffic flows associated with the SLA. The traffic flow attributes may include at least a data rate of a respective traffic flow, an average burst size of the respective traffic flow, and interarrival times of packets associated with the respective traffic flow.

[0088] In some instances, the network parameters and the traffic flow attributes may be obtained based on a slow control loop having relatively slow decision times, and the transmission of traffic flows over the wireless medium may be based on a fast control loop having relatively fast decision times. In some aspects, the transmission mode indications provided by the resource manager may be based on a mid-control loop having decision times that are faster than the relatively slow decision times of the slow control loop, and that are slower than the relatively fast decision times of the fast control loop. In this way, aspects of the present disclosure may provide hierarchical levels of control for selecting or adjusting the transmission modes used for transmitting multiple traffic flows over the wireless medium in a manner that can increase network throughput and/or reduce network latencies (such as compared to conventional techniques based on a single control loop).

[0089] By selecting the transmission modes used for transmitting multiple traffic flows over a wireless medium based on network parameters of one or more wireless networks, one or more traffic flow attributes, or one or more SLA parameters of the traffic flows, an apparatus configured according to various aspects of the present disclosure may concurrently transmit multiple traffic flows over the wireless medium based on a selection of one of SU-MIMO communications, MU-MIMO communications, OFDMA communications, or partial BW MU-MIMO communications that that maximizes network throughput and minimizes network latencies. In addition, the ability to dynamically adjust the transmission mode used for transmitting a respective traffic flow over the wireless medium based on one or more of the network parameters, the traffic flow attributes, or the respective SLA parameters may allow the apparatus to maintain network throughput and latencies when one or more network conditions change. Also, by using a hierarchical control loop to not only obtain network parameters and traffic flow attributes of one or more wireless networks, but also to make transmission mode decisions based at least in part on network parameters and traffic flow attributes observed over relatively long periods of time (e.g., as compared to the relatively short periods of time associated with decision and response times of PHY devices), which may increase the accuracy with which the apparatus determines the most suitable transmission for a particular traffic flow.

[0090] FIG. **7** shows a system **700** of tiered control loops for wireless communication according to some implementations. The example system **700** includes an operator cloud **710** and an AP **720**. In some implementations, the AP **720** may be one example of the AP **102** of FIG. **1**, the wireless communication device **500** of FIG. **5**, or the AP **602** of FIG. **6**A. The operator cloud **710** may represent a backhaul network communicatively coupled to the AP **720** via an external network interface such as, for example, the external network interface **650** of FIG. **6**A. Although not shown for simplicity, the operator cloud **710** may include a network controller or any combination of hardware or software configured to control or manage various operations of the AP **720**.

[0091] The AP **720** is shown to include a resource manager **722**, a kernel **724**, a firmware component **726**, and a hardware component **728**. The firmware component **726** and hardware component **728** represent various components of a wireless communication device such as, for example, the wireless communication device **500** of FIG. **5**. With reference to FIG. **5**, the hardware component **728** may include one or more components of the modem **502** or the radio **504**, and the firmware component **726** may include one or more components of the processor **506** or the memory **508**. In some instances, the hardware component **728** may implement various PHY and MAC layer functionalities associated with transmitting packets over a wireless medium **730**.

[0092] The resource manager **722** represents software executed by a host processor such as, for example, the application processor **630** of FIG. **6**A. In some instances, the resource manager **722** may include instructions stored in memory **640** that can be executed by the application processor **630** to control various operations of the AP **720**. For example, the resource manager **722** may use feedback information provided by the operator cloud **710** and SLAs associated with traffic flows communicated over the wireless medium **730** to select or adjust various settings, parameters, and configurations associated with the transmission of multiple traffic flows over the wireless medium **730** to different STAs (not shown for simplicity).

[0093] The kernel **724** may facilitate interactions between hardware and software components of the AP **720**. For example, the kernel **724** may control various hardware resources of the AP **720** via device drivers, may arbitrate conflicts between hardware resources, and may optimize the utilization of shared resources (such as processor execution cycles, cache memory allocations, file systems, and network sockets). Although not shown in FIG. **7** for simplicity, the kernel **724** may include a host driver, one or more application programming interfaces (APIs), and a MAC Sublayer Management Entity (MLME). In some other aspects, one or more of the host driver, the APIs, or the MLME can be implemented in the resource manager **722**.

[0094] In some implementations, the system **700** may provide hierarchical levels of control for various aspects of wireless communication by the AP **720**. For example, the hardware component **728** may implement one or more "fast" control loops **702** based on feedback provided by the firmware component **726** and/or indications provided by the resource manager **722**. The fast control loops **702** may control resource allocation decisions and transmission mode decisions that require fast convergence. Examples of fast control loops **702** may include just-in-time (JIT) scheduling, smart enhanced distributed channel access (EDCA) adjustments, lazy or aggressive rate control, MU-MIMO or OFDMA grouping, and pausing or unpausing of traffic identifiers (TIDs), among other examples. For example, when implementing a fast control loop **702** associated with MU-MIMO operation, the hardware component **728** may receive, from the resource manager **722**, an indication that MU-MIMO communications are enabled for one or more traffic flows. The hardware component **728** may select MU-MIMO as the transmission mode for the one or more traffic flows based on the indication provided by the resource manager **722**.

[0095] The resource manager **722** and kernel **724** may implement one or more "mid" control loops **704** that determine whether a respective traffic flow is suitable for transmission over the wireless medium **730** as an SU-MIMO communication, as an MU-MIMO communication, as an OFDMA communication, or as a partial BW MU-MIMO communication based on one or more of the network parameters, the traffic flow attributes, or the SLA parameters. In some instances, the mid control loops **704** may control various resource allocation decisions and transmission mode decisions with slower convergence requirements than those associated with the fast control loops **702**. Examples of mid control loops **704** may include multi-link operation (MLO) link provisioning, activating or deactivating multi-link device (MLD) links, enabling or disabling MU communications, enabling or disabling fast rate control, configuring rate control loop constants, configuring maximum data rates, enabling or disabling energy-efficient operation, and configuring uplink (UL) or downlink (DL) throttling limits, among other examples. For example, when implementing a mid-control loop **704** associated with wireless communications, the resource manager **722** may indicate whether or not MU-MIMO communications are enabled for a traffic flow or a group of traffic flows. In this way, the mid control loops **704** may provide a dynamic range of execution for the fast control loops **702**.

[0096] The operator cloud **710** may implement one or more "slow" control loops **706** to obtain network parameters, traffic flow attributes, and other network metrics associated with one or more wireless networks that are monitored by the operator cloud **710**. In some instances, the slow control loops **706** may control various resource allocation decisions and transmission mode decisions with even slower convergence requirements than those associated with the mid control loops **704**. Examples of slow control loops **706** may include setting thresholds for obtaining or otherwise determining one or more LSDs, setting link congestion thresholds and peer reliability thresholds for provisioned MLO, and configuring parameters for managed MU staging, among other examples. For example, when implementing a slow control loop **706** associated with wireless communications, the operator cloud **710** may provide network-level information of at least some of the monitored wireless networks as feedback to the resource manager **722**. In this way, the slow control loops **706** may configure and/or manage one or more decision thresholds for the mid control loops **704**.

[0097] In some implementations, the fast control loops **702** may be configured to make transmission mode decisions for some aspects of wireless communications that require responses between approximately 1 and 100 milliseconds, the mid control loops **704** may be configured to make transmission mode decisions for other aspects of wireless communications that require responses between approximately 1 and 5 seconds, and the slow control loops **706** may be configured to make transmission mode decisions for some other aspects of wireless communications that require responses between approximately 10 and 60 seconds.

[0098] In various implementations, the operator cloud **710** may monitor the interference levels, channel delay spread values (or other indicators of multipath), the number of active STAs, the number or percentage of active STAs that support MU-MIMO communications, the number or percentage of active STAs that support partial BW MU-MIMO communications, the number or percentage of the active STAs that support OFDMA communications, one or more service class parameters, and traffic loads associated with the wireless network operated by the AP **720**, and may provide the resulting network parameters as feedback to the resource manager **722**. The operator cloud **710** may also monitor data rates of the traffic flows, average burst sizes of the traffic flows, average burst periods of the traffic flows, interarrival times of packets associated with the traffic flows, and traffic patterns on the wireless network operated by the AP **720**, and may provide the resulting traffic flow attributes as feedback to the resource manager **722**. In some other implementations, the operator cloud **710** may monitor the network parameters and traffic flow attributes of one or more other wireless networks, and may provide the collective network parameters and traffic flow attributes as additional feedback to the resource manager **722**.

[0099] In some implementations, the resource manager **722** may obtain one or more SLA parameters for each of the traffic flows based on service level agreements between the AP **720** and one or more entities associated with each of the traffic flows. In some aspects, the SLA parameters may specify a minimum data rate for one or more associated traffic flows, a delay bound for one or more associated traffic flows, a service interval for one or more associated traffic flows, a burst size for one or more associated traffic flows, a burst interval for one or more associated traffic flows, and throughput requirements for one or more associated traffic flows, among other examples.

[0100] The resource manager **722** may use one or more of the network parameters provided by the operator cloud **710**, one or more of the traffic flow attributes provided by the operator cloud **710**, and/or one or more SLA parameters for a respective traffic flow to determine whether the respective traffic flow is more likely to achieve higher throughput and lower latencies when transmitted as an SU-MIMO communication, as an MU-MIMO communication, as an OFDMA communication, or as a partial BW MU-MIMO communication. The resource manager **722** may also consider feedback information provided by the fast control loop **702** when determining which transmission mode is most suitable for transmitting the respective traffic flow over the wireless medium. In some instances, the resource manager **722** may also determine whether to enable or disable MU-MIMO communications for each traffic flow to be transmitted over the wireless medium **730** based on one or more of the network parameters, the traffic flow attributes, or the SLA parameters. In various aspects, the resource manager **722** may provide one or more transmission mode indications to the firmware component **726**. For example, in some instances, the resource manager **722** may provide an indication of whether MU-MIMO communications are enabled or disabled for a traffic flow or a group of traffic flows. In other instances, the resource manager **722** may indicate which transmission mode is most likely to maximize throughput and/or to minimize latencies for a particular traffic flow or group of traffic flows.

[0101] As discussed, MU-MIMO communications may achieve higher throughputs and lower latencies than SU-MIMO communications by concurrently transmitting multiple traffic flows over the wireless medium **730** to different users. In some environments, MU-MIMO communications may achieve higher throughputs and lower latencies than OFDMA communications by using spatial diversity, rather than frequency or bandwidth allocations, to accommodate multiple users or traffic flows concurrently. Aspects of the present disclosure recognize that the throughput and latencies associated with MU-MIMO communications may depend on a variety of factors including (but not limited to) interference levels, channel delay spread values, the number of active STAs, the number or percentage of active STAs that support MU-MIMO communications, channel correlation between users grouped for MU communications, the amount of queued DL data available for transmission, specified data rates, specified burst periods, and specified burst sizes, among other examples.

[0102] Specifically, any one or more of relatively high levels of channel correlation between a group of users, relatively high levels of interference, or relatively high levels of channel delay spread may decrease the ability of receiving devices to distinguish between the packets of different traffic flows concurrently transmitted over the wireless medium using MU-MIMO communications, which in turn may decrease throughput and increase latencies associated with such MU-MIMO transmissions. As a result, MU-MIMO communications may not be suitable for transmitting multiple traffic flows over the wireless medium **730** when one or more of these conditions are present. Therefore, in some implementations, the resource manager **722** may disable MU-MIMO communications for transmitting multiple traffic flows over the wireless medium when one or more of the interference levels, channel correlations, or channel delay spread equals or exceeds their respective thresholds. For example, in some instances, the AP **720** may transmit traffic flows as MU-MIMO communications based at least in part on the interference levels being less than an interference threshold, the channel delay spread being less than a value, or both. In other instances, the AP **720** may transmit traffic flows as OFDMA communications based at least in part on the interference levels being at least equal to the interference threshold, the channel delay spread being at least equal to the value, or both.

[0103] In some implementations, the resource manager **722** may also consider the total number of active STAs in the wireless network and the number or percentage of the active STAs that support MU-MIMO communications when indicating a transmission mode for the traffic flow. For example, when the number or percentage of active STAs that support MU-MIMO communications is less than a minimum number, the AP **720** may not be able to group a sufficient number of traffic flows or users for MU communications to compensate for the relatively high overhead of MU-

MIMO communications (such as compared to the overhead of SU-MIMO communications). For another example, although the benefits of MU-MIMO communications may depend on having more than a minimum number of traffic flows or users, the strength and quality of MU-MIMO communications may begin to decrease as the number of nearby active STAs or users increases beyond a certain number. As such, MU-MIMO communications may perform poorly in crowded environments having a dense concentration of wireless devices due to increases in interference, channel correlation, and channel delay spread resulting from the dense concentration of wireless devices, among other examples. Therefore, in some instances, the resource manager **722** may select MU-MIMO communications as the transmission mode for a traffic flow when the number or percentage of active STAs that support MU-MIMO communications equals or exceeds a first number and the total number of active STAs in the wireless network is less than a second number. Conversely, the resource manager **722** may select OFDMA communications as the transmission mode for the traffic flow when the number or percentage of active STAs that support MU-MIMO communications is less than the first number and the total number of active STAs in the wireless network equals or exceeds the second number.

[0104] Aspects of the present disclosure also recognize that MU-MIMO communications are well-suited for traffic flows that have relatively high data rates, which have a relatively low level of burstiness, and that can provide sufficient amounts of queued DL data in the AP **720** to compensate for the relatively high overhead of MU-MIMO communications. As such, in some implementations, the resource manager **722** may enable MU-MIMO communications for traffic flows having high data rates, having packet interarrival times offset in time from each other by less than a threshold time period, having average burst sizes at least equal to a burst size threshold, or any combination thereof. In some aspects, the decision to enable MU-MIMO communications for a respective traffic flow may also be based on the minimum data rate specified by the SLA being at least equal to a data rate threshold, the maximum delay bound specified by the SLA being at least equal to a delay period, the throughput requirement specified by the SLA being at least equal to a throughput threshold, or any combination thereof. In other implementations, the resource manager **722** may indicate that a traffic flow is suitable for transmission over the wireless medium **730** to one or more associated STAs as an MU-MIMO communication when the interarrival times of its respective packets are offset in time from each other by less than a threshold time period, when the average burst size equals or exceeds a burst size threshold, or both.

[0105] On the other hand, MU-MIMO communications may not be well-suited for transmitting a traffic flow having a relatively small burst size and a relatively long burst interval, for example, because the relatively high level of burstiness of the traffic flow may preclude, or at least decrease the likelihood of, grouping packets of the traffic flow with packets of one or more other traffic flows for MU transmissions. Therefore, in some implementations, the resource manager **722** may disable MU-MIMO communications for traffic flows having low data rates, having packet interarrival times offset in time from each other by more than the threshold time period, having average burst sizes less than the burst size threshold, or any combination thereof. In some instances, the resource manager **722** may select OFDMA or partial BW MU-MIMO as the transmission mode for transmitting such traffic flows over the wireless medium **720** to one or more associated STAs.

[0106] Also, MU-MIMO communications may not be well-suited for transmitting a traffic flow having strict latency requirements, for example, because the strict latency requirements may limit the time period by which the AP **720** can delay the transmission of queued packets of the traffic flow for possible grouping with other packets received by the AP **720** during the time period, which in turn decreases the likelihood of grouping the traffic flow with one or more other traffic flows for transmission over the wireless medium **730** as an MU-MIMO communication. As such, in some implementations, the resource manager **722** may disable MU-MIMO communications for traffic flows having a maximum latency tolerance less than a threshold latency. In some instances, the resource manager **722** may select OFDMA or partial BW MU-MIMO as the transmission mode for transmitting such traffic flows over the wireless medium **720** to one or more associated STAs.

[0107] In some implementations, the resource manager **722** may disable MU-MIMO communications for latency-sensitive traffic flows, for example, because latency-sensitive traffic flows typically have strict timing, throughput, and latency requirements that preclude, or at least decrease the likelihood of, grouping such traffic flows with each other and/or with other traffic flows for MU transmissions. In other implementations, the resource manager **722** may disable MU-MIMO communications only for latency-sensitive traffic flows having an amount of queued data that is less than the data threshold. Specifically, in some instances, the resource manager **722** may select MU-MIMO communications as the transmission mode for latency-sensitive traffic flows having an amount of queued data equal to or exceeding the data threshold, or may select OFDMA communications as the transmission mode for latency-sensitive traffic flows having an amount of queued data less than the data threshold. In some aspects, the resource manager **722** may select partial BW MU-MIMO communications as the transmission mode for latency-sensitive traffic flows when the number of active latency-sensitive traffic flows equals or exceeds a threshold number of traffic flows. On the other hand, the resource manager **722** may select OFDMA communications as the transmission mode for some latency-sensitive traffic flows when the number of active latency-sensitive traffic flows is less than the threshold number of traffic flows.

[0108] FIG. **8** shows a block diagram of an apparatus **800** associated with a slow control loop **801**, a mid-control loop **802**, and a fast control loop **803** of an AP, according to some implementations. In some implementations, the apparatus may be an AP such one of the APs **102**, **602**, and **720** of FIGS. **1**, **6**A, and **7**, respectively. In various aspects, the slow control loop **801** may be associated with one or more application programming interfaces (APIs) **810** of the apparatus **800**, and in some instances, may also be associated with the operator cloud **710** described with reference to FIG. **7**. The mid control loop **802** may be associated with a resource manager **820** of the apparatus **800**, and the fast control loop **803** may be associated with a firmware and hardware component **830** of the apparatus **800**.

[0109] The APIs **810** may provide an interface through which the resource manager **820** can obtain network parameters and traffic flow attributes for one or more wireless networks monitored by the operator cloud **710**. The APIs **810** may also provide an interface through which the resource manager **820** may obtain one or more SLA parameters for each of the traffic flows communicated over the wireless medium **730**. In some aspects, the APIs **810** may be one example of the APIs described with reference to FIG. **6**. For example, the APIs **810** may include an MLME API, a time sectoring API, an MU API, a resource manager telemetry API, a T2LM API, and one or more provisioning APIs, among other examples. In some instances, the one or more provisioning APIs may be used either independent of, or in conjunction with, the resource manager **820** to select or adjust the transmission modes used for transmitting traffic flows over the wireless medium **730**. In other instances, the one or more provisioning APIs may be used either independent of, or in conjunction with, the resource manager **820** to provide indications of whether a respective traffic flow is more suitable for transmission over the wireless medium **730** as an SU-MIMO communication, as an MU-MIMO communication, as an OFDMA communication, or as a partial BW MU-MIMO communication.

[0110] In some implementations, the provisioning APIs may be instructed by the resource manager **820** to configure various aspects of the firmware and hardware component **830** based on the mid control loop **802**. For example, the resource manager **820** may instruct the provisioning APIs to select or adjust the transmission mode used for transmitting traffic flows over the wireless medium **730**, to select or adjust one or more of the thresholds used to determine whether a traffic flow is more suited for transmission over the wireless medium **730** as an SU-MIMO communication, as an MU-MIMO communication, as an OFDMA communication, or as a partial BW MU-MIMO communication, or to select or adjust the MCS used for transmitting traffic flows over the wireless medium **730**. In some instances, the resource manager **820** may also instruct the provisioning APIs to assign a transmission mode to a particular packet queue, to select or adjust one or more data thresholds associated with the packet queues, or to select or adjust one or more delay periods associated with the packet queues or associated with traffic flows communicated over the wireless network.

[0111] The resource manager **820**, which may be one example of the resource manager **722** of FIG. **7**, is shown to include a network time sectoring component **822**, an MU enablement component **824**, and a dynamic MU staging component **826**, among other components. The network time sectoring component **822** may divide a BSS (such as the BSS operated by the AP **720** of FIG. **7**) into a number of time sectors, where each of the time sectors represents a respective interval of time that occurs periodically and does not overlap any of the other time sectors. In various aspects, the network time sectoring component **822** maps each of its associated STAs to one or more of the time sectors so that at least one STA is mapped to each time sector. For example, in some instances, the network time sectoring component **822** may map its associated STAs to the time sectors in order of association identifier (AID) values. In other instances, the network time sectoring component **822** may map its associated STAs to the time sectors based on one or more attributes or parameters of the BSS. Example attributes may include a volume of data traffic communicated with each STA, a direction of communications with each STA, capabilities supported by each STA, PHY modes supported by each STA, QoS requirements associated with each STA, network topology characteristics associated with each STA, channel characteristics associated with each STA, and SLA requirements associated with each STA, among other examples. In some aspects, network time sectoring component **822** may provision resources for communications with each of the associated STAs so that any communications with a given STA occur only during the time sector(s) to which the STA is mapped (and not during any time sectors to which the STA is not mapped). In various aspects, the network time sectoring component **822** provides an indication of the provisioned resources, including resource mapping and allocations, to the firmware and hardware component **830**.

[0112] The MU enablement component **824** may implement any one or more of the operations performed by the resource manager **722** described with reference to FIG. **7**. For example, the MU enablement component **824** may determine whether traffic flows associated with packets queued for transmission in the AP are suitable for transmission over the wireless medium **730** as SU-MIMO communications, as MU-MIMO communications, as OFDMA communications, or as partial BW MU-MIMO communications. In some instances, the MU enablement component **824** may use one or more of the network parameters, the traffic flow attributes, or the SLA parameters of a traffic flow to select one of SU-MIMO, MU-MIMO, OFDMA, or partial BW MU-MIMO as the transmission mode for the traffic flow. The MU enablement component **824** may also determine whether or not to enable MU-MIMO communications for a particular traffic flow or group of traffic flows based on one or more of the network parameters, the traffic flow attributes, or the SLA parameters. In some aspects, the MU enablement component **824** may indicate the respective transmission modes of traffic flows to the network time sectoring component **822**, to the dynamic MU staging component **826**, or both. In some implementations, the MU enablement component **824** may determine which traffic flows are candidates for MU grouping, and may provide an indication of the candidate traffic flows to the network time sectoring component **822**, to the dynamic MU staging component **826**, or both.

[0113] The dynamic MU staging component **826** may group packets associated with different traffic flows with one another for transmission over the wireless medium **730** as an MU-MIMO communication. Specifically, the dynamic MU staging component **826** may receive indications of which traffic flows are candidates for MU grouping from the MU enablement component **824**, and may determine whether a sufficient number of queued packets associated with at least two of the candidate traffic flows can be grouped with one another and concurrently transmitted over the wireless medium **730** as an MU-MIMO communication. In some aspects, the grouped packets may be transmitted over the wireless medium **730** as one or more MU PPDUs formatted according to the IEEE 802.11 family of wireless communication standards. In some aspects, the dynamic MU staging component **826** may also determine the amount of available space in the packet queues associated with the AP. The dynamic MU staging component **826** may provide the MU groupings and indications of available space in the respective packet queues to the firmware and hardware component **830**.

[0114] In various implementations, the dynamic MU staging component **826** may delay transmission of queued DL packets associated with a respective traffic flow for a delay period during which additional packets of the respective traffic flow and/or other packets associated with one or more other candidate traffic flows may be received and buffered in the packet queues. When these additional and/or other packets are received by the AP and available for transmission prior to expiration of the delay period, the dynamic MU staging component **826** may group the queued packets of the respective traffic flow with the additional packets of the respective traffic flow and/or the other packets associated with other traffic flows for transmission over the wireless medium **730** as an MU-MIMO communication. In some instances, the dynamic MU staging component **826** may group up to a number N of the traffic flows for transmission as an MU-MIMO communication, where the number N indicates the maximum number of users that can be grouped in a single MU PPDU. For example, the maximum number of users that can be grouped in an MU PPDU by an AP operating according to the 802.11ax and 802.11be amendments to the IEEE 802.11 standard is N=8.

[0115] In some implementations, the dynamic MU staging component **826** may determine whether or not to delay transmission of the queued packets for the delay period based at least in part on the amount of data carried in the queued packets being less than a queue data threshold associated with the respective traffic flow. The queue data threshold may correspond to a minimum amount or minimum transit duration of data carried by the queued packets to enable MU-MIMO communications for the respective traffic flow. In some instances, the queue data threshold may also be based at least in part on the available space of the packet queues. For example, in some aspects, the dynamic MU staging component **826** may increase the queue data threshold when the available space in the corresponding packet queue is relatively high (such as greater than a value), or may decrease the queue data threshold when the available space in the corresponding packet queue is relatively low (such as less than the value). By increasing the queue data threshold for enabling MU-MIMO communications when the available space in the corresponding packet queue is relatively high, the dynamic MU staging component **826** may increase the efficiency with which different traffic flows may be grouped with one another for MU-MIMO communications. Conversely, by decreasing the queue data threshold for enabling MU-MIMO communications when available space in the corresponding packet queue is relatively low, the dynamic MU staging component **826** may increase the likelihood of grouping different traffic flows with one another for MU-MIMO communications.

[0116] In other instances, the queue data threshold may also be based at least in part on the BSS load of the AP. For example, in some aspects, the dynamic MU staging component **826** may increase the queue data threshold when the BSS load is relatively high (such as greater than a value), or may decrease the queue data threshold when the BSS load is relatively low (such as less than the value). By increasing the queue data threshold for enabling MU-MIMO communications when the BSS load is relatively high, the dynamic MU staging component **826** may increase the efficiency with which different traffic flows may be grouped with one another for MU-MIMO communications. Conversely, by decreasing the queue data threshold for enabling MU-MIMO communications when the BSS load is relatively low, the dynamic MU staging component **826** may increase the likelihood of grouping different traffic flows with one another for MU-MIMO communications.

[0117] The delay period may be any suitable time period that is less than the delay bound specified by the SLA parameters for a respective traffic flow. In this way, the AP may delay the transmission of one or more queued packets of a respective traffic flow for a possible MU grouping with additional packets of the respective traffic flow and/or with other packets associated with other traffic flows without violating the latency requirements associated with the respective traffic flow. In some aspects, the delay period may be set to zero, for example, to indicate that the queued packets are to be transmitted as an SU-MIMO communication when available for transmission (e.g., rather than delaying their transmission for possible MU groupings with yet-to-be received packets). The dynamic MU staging component **826** may provide the delay period associated with each traffic flow communicated over the wireless medium **730** to the firmware and hardware component **830**.
[0118] In some implementations, the delay period may be based on one or more of the BSS load of the AP, the available space in the packet queues, or the minimum data rate of the respective traffic flow. For example, in some instances, the dynamic MU staging component **826** may increase the delay period when the minimum data rate specified by the SLA parameters for the respective traffic flow is relatively high (such as greater than a value), or may decrease the delay period when the minimum data rate specified by the SLA parameters for the respective traffic flow is relatively low (such as less than the value). In other instances, the dynamic MU staging component **826** may increase the delay period when the BSS load of the AP is relatively low (such as less than a value), or may decrease the delay period when the BSS load of the AP is relatively high (such as greater than the value). Specifically, by increasing the delay period when the BSS load is relatively low, the dynamic MU staging component **826** may increase the likelihood of grouping different traffic flows with one another for MU-MIMO communications. Conversely, by decreasing the delay period when the BSS load is relatively low, the dynamic MU staging component **826** may increase the efficiency with which different traffic flows may be grouped with one another for MU-MIMO communications.
[0119] In various implementations, the dynamic MU staging component **826** can obtain, from the firmware and hardware component **830** (or other components of the fast loop **803**), feedback information indicating that at least a number or percentage of the MU-MIMO candidate traffic flows are not being grouped with one another for MU-MIMO transmissions prior to expiration of the respective delay periods of the MU-MIMO candidate traffic flows. In some aspects, the dynamic MU staging component **826** may adjust one or more of the respective delay period, the respective first threshold, or the respective second threshold associated with each of the traffic flow of the number or percentage of traffic flows based on the feedback information. In this way, the dynamic MU staging component **826** can determine the effectiveness of information provided by components of the mid loop **802** for grouping traffic flows together for MU-MIMO transmissions.
[0120] The firmware and hardware component **830**, which may be an example of the firmware component **726** and the hardware component **728** described with reference to FIG. **7**, is shown to include a QoS scheduler **832**, a Tx Mode selection component **834**, and an MU scheduler **836**, among other components. The QoS scheduler **832** may obtain feedback information and indications from the resource manager **820** based on the mid control loop **802**, and use the feedback information and indications to schedule the transmission of packets associated with different traffic flows in a manner that complies with various QoS parameters for each of the different traffic flows. In some instances, the QoS scheduler **832** may assign a transmission mode to the packet queues associated with each traffic flow based at least in part on the indications provided by the MU enablement component **834**.
[0121] The Tx Mode selection component **834** may select or adjust the transmission mode for transmitting one or more traffic flows over the wireless medium **730** based on indications provided by the resource manager **820**. In some instances, the Tx Mode selection component **834** may instruct or configure various MAC and PHY components of the AP to implement the transmission

mode indicated by the resource manager **820**. For example, when indications provided by the resource manager **722** select SU-MIMO as the transmission mode for a traffic flow, the Tx Mode selection component **834** may configure the MAC and PHY components of the AP, as well as any associated antenna resources (not shown for simplicity), for the transmission of one or more SU PPDUs over the wireless medium **730**. Similarly, when indications provided by the resource manager **722** select OFDMA as the transmission mode for a traffic flow, the Tx Mode selection component **834** may configure the MAC and PHY components of the AP, as well as the associated antenna resources, for the transmission of one or more groups of MU PPDUs over the wireless medium **730**.

[0122] For another example, when indications provided by the resource manager **722** select MU-MIMO as the transmission mode for a traffic flow, the Tx Mode selection component **834** may obtain MU grouping information and transmission delays (e.g., the delay times) associated with the traffic flow from the dynamic MU staging component **826**, and configure the MAC and PHY components of the AP, as well as the associated antenna resources, for the transmission of one or more MU PPDUs over the wireless medium **730**. Similarly, when indications provided by the resource manager **722** select partial BW MU-MIMO as the transmission mode for a traffic flow, the Tx Mode selection component **834** may obtain MU grouping information and transmission delays associated with the traffic flow from the dynamic MU staging component **826**, and may obtain resource mappings and allocations from the network time sectoring component **822**. The Tx Mode selection component **834** may configure the MAC and PHY components of the AP, as well as the associated antenna resources, for the transmission of one or more groups of MU PPDUs over one or more respective frequency allocations of the wireless medium **730**.

[0123] The MU scheduler **836** may include, or may be associated with, a plurality of packet queues that can store and buffer incoming packets associated with multiple traffic flows for transmission over the wireless medium **730** to one or more STAs or groups of STAs. In various implementations, the MU scheduler **836** may delay the transmission of one or more groups of packets queued in the packet queues based on indications provided by the MU enablement logic **834** and the dynamic staging component **826**.

[0124] FIG. **9**A shows a timing diagram depicting an example communication **900**, according to some implementations. The wireless communication **900** may be performed between an AP and two stations, STA**1** and STA**2**. The AP may be any suitable access point, access terminal, base station, or apparatus that implements the corresponding AP. In some instances, the AP may be one example of the AP **102** of FIG. **1**, the AP **602** of FIG. **6**A, the AP **720** of FIG. **7**, or the apparatus **800** of FIG. **8**. Each of STA**1**-STA**2** may be any suitable station, client device, user equipment (UE), or apparatus that implements the STA. In some instances, each of STA**1**-STA**2** may be an example of the STAs **104** of FIG. **1** or the STA **604** of FIG. **6**B. Although only two stations STA**1**-STA**2** are shown in the example of FIG. **9**A, in some other implementations, the BSS operated by the AP may include any suitable number of STAs.

[0125] In the example of FIG. **9**A, the AP transmits groups of SU PPDUs **901**, **902**, and **903** over a wireless medium to STA**1** between times t.sub.0-t.sub.1, between times t.sub.4-t.sub.5, and between times t.sub.6-t.sub.7, respectively. The AP also transmits groups of SU PPDUs **911** and **912** over the wireless medium to STA**2** between times t.sub.2-t.sub.3 and between times t.sub.8-t.sub.9, respectively. In some instances, the groups of SU PPDUs **901**, **902**, and **903** may be associated with a first traffic flow intended for STA**1**, and the groups of SU PPDUs **911** and **912** may be associated with a second traffic flow intended for STA**2**.

[0126] Specifically, beginning at time t.sub.0, PPDUs **901** of the first traffic flow are received and buffered in a first packet queue of the AP until the amount of data carried in the queued PPDUs **901** equals or exceeds a queue data threshold of the first traffic flow, at time t.sub.1. In some instances, the queue data threshold of the first traffic flow may correspond to an amount of data that can be carried in the group of SU PPDUs **901**. At time t.sub.1, the AP transmits the queued PPDUs **901** over the wireless medium to STA**1** as an SU-MIMO communication.

[0127] Beginning at time t.sub.2, PPDUs **911** of the second traffic flow are received and buffered in a second packet queue of the AP until the amount of data carried in the queued PPDUs **911** equals or exceeds a queue data threshold of the second traffic flow, at time t.sub.3. In some instances, the queue data threshold of the second traffic flow may correspond to an amount of data that can be carried in the group of SU PPDUs **911**. At time t.sub.3, the AP transmits the queued PPDUs **911** over the wireless medium to STA**2** as an SU-MIMO communication.

[0128] Beginning at time t.sub.4, additional PPDUs **902** of the first traffic flow are received and buffered in the first packet queue of the AP until the amount of data carried in the queued PPDUs **902** equals or exceeds the queue data threshold of the first traffic flow. At time t.sub.5, the AP transmits the queued PPDUs **902** over the wireless medium to STA**1** as an SU-MIMO communication.

[0129] Beginning at time t.sub.6, additional PPDUs **903** of the first traffic flow are received and buffered in the first packet queue of the AP until the amount of data carried in the queued PPDUs **903** equals or exceeds the queue data threshold of the first traffic flow. At time t.sub.7, the AP transmits the queued PPDUs **903** over the wireless medium to STA**1** as an SU-MIMO communication.

[0130] Beginning at time t.sub.8, additional PPDUs **912** of the second traffic flow are received and buffered in the second packet queue of the AP until the amount of data carried in the queued PPDUs **912** equals or exceeds the queue data threshold of the second traffic flow. At time t.sub.9, the AP transmits the queued PPDUs **912** over the wireless medium to STA**2** as an SU-MIMO communication.

[0131] As depicted in the example of FIG. **9**A, each transmission of PPDUs to STA**1** is an SU transmission that precludes other transmissions over the wireless medium, and each transmission of PPDUs to STA**2** is an SU transmission that precludes other transmissions over the wireless medium. That is, while the SU PPDUs **901**, **902**, and **903** are transmitted over the wireless medium between respective times t.sub.0-t.sub.1, t.sub.4-t.sub.5, and times t.sub.6-t.sub.7, none of the other STAs (including STA**2**) may use the wireless medium. Similarly, while the SU PPDUs **911** and **912** are transmitted over the wireless medium between respective times t.sub.2-t.sub.3 and t.sub.8-t.sub.9, none of the other STAs (including STA**1**) may use the wireless medium. As such, transmitting multiple traffic flows over the wireless medium using SU-MIMO communications may not result in an efficient use of the wireless medium.

[0132] FIG. **9**B shows a timing diagram depicting an example communication **950**, according to other implementations. The example communication **950** may be performed between the AP and STA**1**-STA**2** described with reference to FIG. **9**A. In the example of FIG. **9**B, the AP delays transmission of the PPDUs **901** of the first traffic flow by a delay period so that the PPDUs **901** can be grouped with the PPDUs **911** of the second traffic flow and concurrently transmitted over the wireless medium as one or more MU PPDUs **951** between times t.sub.2-t.sub.3. Similarly, the AP delays transmission of the PPDUs **902** and **903** of the first traffic flow by respective delay periods so that the PPDUs **902** and **903** can be grouped with the PPDUs **912** of the second traffic flow and concurrently transmitted over the wireless medium as one or more MU PPDUs **952** between times t.sub.8-t.sub.9.

[0133] Specifically, the AP begins receiving and buffering PPDUs **901** of the first traffic flow into a first packet queue at time t.sub.0, and continues filling the first packet queue with the PPDUs **901** until time t.sub.1, at which point the amount of data carried by the queued PPDUs **901** equals or exceeds a first queue data threshold. In some implementations, the first queue data threshold may correspond to a minimum amount or minimum transit duration of data carried by the queued PPDUs **901** to enable MU-MIMO communications for the first traffic flow. At time t.sub.1, the AP designates the queued PPDUs **901** of the first traffic flow as a candidate for MU-MIMO communications, and delays transmission of the queued PPDUs **901** by a delay period **961**. Thus, although the AP may transmit the queued PPDUs **901** as an SU-MIMO communication to STA**1** at time t.sub.1, the AP delays transmission of the queued PPDUs **901** for the delay period **961** during which the AP may receive additional packets of the first traffic flow and/or other packets associated with one or more other traffic flows. These additional and/or other packets, if received by the AP and available for transmission prior to expiration of the delay period **961**, may be grouped with the queued PPDUs **901** of the first traffic flow and transmitted over the wireless medium as an MU-MIMO communication. In this way, aspects of the present disclosure may increase the likelihood of grouping packets associated with multiple traffic flows in a manner that allows the grouped packets of the multiple traffic flows to be concurrently transmitted over the wireless medium using MU-MIMO transmissions, which as discussed above may achieve higher throughputs and lower latencies than SU-MIMO transmissions.

[0134] The delay period **961** may be any suitable time period that is less than the delay bound specified by the SLA parameters for the first traffic flow. In this way, aspects of the present disclosure may delay transmission of the queued PPDUs **901** for a possible MU grouping with other packets received during the delay period **961** without violating the latency requirements associated with the first traffic flow. Although not shown in FIG. **9**B for simplicity, in some aspects, the delay period **961** may be set to zero, for example, to indicate that the queued PPDUs **901** are to be transmitted as an SU-MIMO communication when available for transmission, rather than delaying transmission for a possible MU grouping.

[0135] During the delay period **961**, at time t.sub.2, the AP begins receiving and buffering PPDUs **911** of the second traffic flow into a second packet queue. By time t.sub.3, the amount of data carried by the queued PPDUs **911** equals or exceeds a second queue data threshold. In some instances, the second queue data threshold may correspond to a minimum amount or minimum transit duration of data carried by the queued PPDUs **911** to enable MU-MIMO communications for the second traffic flow. In response thereto, the AP groups the queued PPDUs **901** of the first traffic flow with the queued PPDUs **911** of the second traffic flow for transmission over the wireless medium as an MU-MIMO communication. Specifically, at time t.sub.3, the AP embeds the queued PPDUs **901** and PPDUs **911** into one or more MU PPDUs **951**, and transmits the MU PPDUs **951** over the wireless medium to STA**1** and STA**2** as an MU-MIMO communication. In this way, the PPDUs **901** of the first traffic flow may be transmitted to STA**1** concurrently with the transmission of PPDUs **911** of the second traffic flow to STA**2**.

[0136] In other implementations, the first queue data threshold may also be based on the available space in the first packet queue, and the second queue data threshold may also be based on the available space in the second packet queue. For example, in some instances, the resource manager of the AP may increase the first queue data threshold when the available space in the first packet queue is relatively high (such as greater than a first value), and may increase the second queue data threshold when the available space in the second packet queue is relatively high (such as greater than a second value). Conversely, the resource manager of the AP may decrease the first queue data threshold when the available space in the first packet queue is relatively low (such as greater than the first value), and may decrease the second queue data threshold when the available space in the second packet queue is relatively low (such as less than the second value). In this way, aspects of the present disclosure may use the mid-control loops disclosed herein to adjust the queue data thresholds of an AP's packet queues based on the available space in the respective packet queues.

[0137] In some other implementations, the first and second queue data thresholds may also be based on the BSS load of the AP. In some instances, when the BSS load is relatively high (such as greater than a value), the resource manager of the AP may increase the first and second queue data thresholds, for example, because there is more traffic on the wireless medium available for possible MU grouping with the queued PPDUs. In this way, the resource manager of the AP may increase the efficiency with which queued PPDUs associated with different traffic flows can be grouped together for concurrent transmission over the wireless medium as an MU-MIMO communication when the BSS load is relatively high. Conversely, when the BSS load is relatively low (such as less than the value), the resource manager of the AP may decrease the first and second queue data thresholds, for example, because there is less traffic on the wireless medium available for possible MU grouping with the queued PPDUs. In this way, the resource manager of the AP may increase the likelihood of grouping the queued PPDUs associated with different traffic flows for concurrent transmission over the wireless medium as an MU-MIMO communication when the BSS load is relatively low. In some aspects, aspects of the present disclosure may use the mid-control loops disclosed herein to adjust the queue data thresholds of an AP's packet queues based on the BSS load associated with the AP.

[0138] At time t.sub.4, the AP begins receiving and buffering PPDUs **902** of the first traffic flow into the first packet queue, and continues filling the first packet queue with the PPDUs **902** until time t.sub.5. Then, at time t.sub.5, the AP delays transmission of the queued PPDUs **902** by a delay period **962** during which the AP may receive additional packets of the first traffic flow and/or other packets associated with one or more other traffic flows. These additional and/or other packets, if received by the AP and available for transmission prior to expiration of the delay period **962**, may be grouped with the queued PPDUs **902** of the first traffic flow and transmitted over the wireless medium as an MU-MIMO communication. In some instances, the amount of data carried by the queued PPDUs **902** may equal or exceed the first queue data threshold at time t.sub.5, and the AP may designate the queued PPDUs **902** as candidates for MU-MIMO communications. In other instances, the amount of data carried by the queued PPDUs **902** may be less than the first queue data threshold at time t.sub.5, and the AP may not designate the queued PPDUs **902** as candidates for MU-MIMO communications. In some aspects, the AP may not designate the first traffic flow as eligible for MU-MIMO communications until enough additional PPDUs of the first traffic flow are received and buffered in the first packet queue such that the total amount of queued data associated with the first traffic flow equals or exceeds the first queue data threshold.

[0139] During the delay period **962**, at time t.sub.6, the AP begins receiving and buffering additional PPDUs **903** of the first traffic flow into the first packet queue. By time t.sub.7, the amount of data carried by the queued PPDUs **902** and **903** of the first traffic flow equals or exceeds the first queue data threshold. At time t.sub.7, the AP designates the queued PPDUs **902** and **903** of the first traffic flow as a candidate for MU-MIMO communications, and delays transmission of the queued PPDUs **902** and **903** for a remainder of the delay period **962**. Thus, although the AP may transmit the queued PPDUs **902** and **903** as an SU-MIMO communication to STA**1** at time t.sub.7, the AP delays transmission of the queued PPDUs **902** and **903** for the remainder of the delay period **962** during which the AP may receive additional packets of the first traffic flow and/or other packets associated with one or more other traffic flows. These additional and/or other packets, if received by the AP and available for transmission prior to expiration of the delay period **962**, may be grouped with the queued PPDUs **902** and **903** of the first traffic flow and transmitted over the wireless medium as an MU-MIMO communication. In this way, aspects of the present disclosure may increase the likelihood of grouping packets associated with multiple traffic flows in a manner that allows the grouped packets of the multiple traffic flows to be concurrently transmitted over the wireless medium using MU-MIMO transmissions, which as discussed above may achieve higher throughputs and lower latencies than SU-MIMO transmissions.

[0140] At time t.sub.8, which occurs within the delay period **962**, the AP begins receiving and buffering PPDUs **912** of the second traffic flow into the second packet queue. By time t.sub.9, the amount of data carried by the queued PPDUs **912** of the second traffic flow equals or exceeds the second queue data threshold. As discussed, the second queue data threshold may correspond to a minimum amount or minimum transit duration of data carried by the queued PPDUs **912** to enable MU-MIMO communications for the second traffic flow. In response thereto, the AP groups the queued PPDUs **902** and **903** of the first traffic flow with the queued PPDUs **912** of the second traffic flow for transmission over the wireless medium as an MU-MIMO communication.

Specifically, at time t.sub.9, the AP embeds the queued PPDUs **902**, **903**, and **912** into one or more MU PPDUs **952**, and transmits the MU PPDUs **952** over the wireless medium to STA**1** and STA**2** as an MU-MIMO communication. In this way, the PPDUs **902** and **903** of the first traffic flow may be transmitted to STA**1** concurrently with the transmission of PPDUs **912** of the second traffic flow to STA**2**.

[0141] As discussed, the delay periods **961** and **962** may be any suitable time periods that are less than the delay bound specified by the SLA parameters for the first traffic flow, for example, so that the AP may delay the transmission of queued PPDUs of the first traffic flow for a possible MU grouping with other packets received during the respective delay periods **961** and **962** without violating the latency requirements associated with the first traffic flow.

[0142] In some implementations, the delay periods **961** and **962** may be adjusted based, at least in part, on the minimum data rate specified by the SLA parameters for the first traffic flow. For example, in some instances, the resource manager of AP may increase the delay periods **961** and **962** when the minimum data rate specified by the SLA parameters for the first traffic flow is relatively high (such as greater than a value). Conversely, the resource manager of the AP may decrease the delay periods **961** and **962** when the minimum data rate specified by the SLA parameters for the first traffic flow is relatively low (such as less than the value). In this way, aspects of the present disclosure may use the mid-control loops disclosed herein to adjust the delay period of a traffic flow based on the minimum data rate specified for the traffic flow.

[0143] In some other implementations, one or more of the first queue data threshold, the second queue data threshold, the delay period **961**, or the delay period **926** may be adjusted by the slow control loops disclosed herein. Specifically, in some instances, the slow control loops disclosed herein may adjust one or more of the first queue data threshold, the second queue data threshold, the delay period **961**, or the delay period **926** based at least in part on one or more of the number of traffic flows that are designated as candidates for MU grouping, an average data rate of the STAs for which the candidate traffic flows are intended, an average amount of data received by the STAs for which the candidate traffic flows are intended, channel conditions of the wireless medium, a level of contention on the wireless medium, a level of interference on the wireless medium, or a channel occupancy of the wireless medium. For example, in some aspects, the resource manager of the AP may increase the delay periods **961** and **962** based on indications from the operator cloud **710** that the average data rate of the STAs receiving the respective traffic flow is relatively high (such as greater than a value), or may decrease the delay periods **961** and **962** based on indications from the operator cloud **710** that the average data rate of the STAs receiving the respective traffic flow is relatively low (such as less than the value). For another example, in some aspects, the resource manager of the AP may increase the delay periods **961** and **962** based on indications from the operator cloud **710** that the number of traffic flows designated as MU grouping candidates is relatively low (such as less than a value), or may decrease the delay periods **961** and **962** based on indications from the operator cloud **710** that the number of traffic flows designated as MU grouping candidates is relatively high (such as greater than the value). For another example, in other aspects, the resource manager of the AP may increase the delay periods **961** and **962** based on indications from the operator cloud **710** that one or more of the channel conditions, contention levels, interference levels, or channel occupancy of the wireless medium is relatively high (such as greater less than a level), or may decrease the delay periods **961** and **962** based on indications from the operator cloud **710** that one or more of the channel conditions, contention levels, interference levels, or channel occupancy of the wireless medium is relatively low (such as less than the level).

[0144] In various implementations, the resource manager of the AP may obtain feedback information from the fast control loops disclosed herein indicating that at least a number or percentage of the traffic flows communicated over the wireless medium are not being grouped with one another for MU-MIMO transmissions prior to expiration of the delay periods **961** and **962**. In some aspects, the resource manager may adjust one or more of the first queue data threshold, the second queue data threshold, the delay period **961**, or the delay period **962** based on the feedback information. For example, in some instances, the resource manager may decrease the first and second queue data thresholds when the number or percentage of traffic flows not being grouped with one another for MU-MIMO transmissions prior to expiration of the delay periods is relatively high (such as greater than a first number). In some aspects, the resource manager may also increase the delay periods **961** and **962** when the number or percentage of traffic flows not being grouped with one another for MU-MIMO transmissions prior to expiration of the delay periods is relatively high.

[0145] Conversely, the resource manager may increase the first and second queue data thresholds when the number or percentage of traffic flows not being grouped with one another for MU-MIMO transmissions prior to expiration of the delay periods is relatively low (such as less than a second number that is lower than the first number). In some aspects, the resource manager may also decrease the delay periods **961** and **962** when the number or percentage of traffic flows not being grouped with one another for MU-MIMO transmissions prior to expiration of the delay periods is relatively low. In this way, aspects of the present disclosure may increase the likelihood of grouping different traffic flows with one another for MU-MIMO communications when the number or percentage of traffic flows not being grouped with one another for MU-MIMO transmissions prior to expiration of the delay periods is relatively high, or may increase the efficiency with which different traffic flows may be grouped with one another for MU-MIMO communications when the number or percentage of traffic flows not being grouped with one another for MU-MIMO transmissions prior to expiration of the delay periods is relatively low.

[0146] As discussed, the resource manager of the AP may adjust one or more of the first queue data threshold, the second queue data threshold, the delay period **961**, or the delay period **962** based on network telemetry and other feedback information provided by the slow control loops disclosed herein. In this way, aspects of the present disclosure may use various network parameters, traffic flow attributes, and traffic patterns observed over relatively long periods of time associated with the slow control loops to fine tune one or more corresponding coarse adjustments to the queue data thresholds or delay periods facilitated by the mid-control loops and/or fast control loops disclosed herein. These fine tune adjustments to the queue data thresholds or delay periods may increase the efficiency with which APs can identify and group multiple traffic flows with one another for transmission over the wireless medium as MU-MIMO communications.

[0147] FIG. **10** shows a timing diagram depicting an example wireless communication **1000** that supports grouping multiple traffic flows together for MU-MIMO communications, according to some implementations. The wireless communication **1000** may be performed between an AP and three stations STA**1**-STA**3**. The AP may be any suitable access point, access terminal, base station, or an apparatus that implements the AP. In some instances, the AP may be one example of the AP **102** of FIG. **1**, the AP **602** of FIG. **6**A, the AP **720** of FIG. **7**, or the apparatus of FIG. **8**. Each of STA**1**-STA**3** may be any suitable wireless station, client device, user equipment (UE), or an apparatus that implements the STA. In some instances, each of the STA**1**-STA**3** may be an example of the STAs **104** of FIG. **1** or the STA **604** of FIG. **6**B.

[0148] The example of FIG. **10** shows a first packet queue Q**1**, a second packet queue Q**2**, a third packet queue Q**3**, and a transmitter **1010** of the AP. In various implementations, the packet queues Q**1**-Q**3** may be implemented in the hardware component **728** of the AP **720** of FIG. **7** or the hardware component **830** of the apparatus **800** of FIG. **8**. In some other instances, the packet queues Q**1**-Q**3** may be implemented in the MAC layer and/or the PHY of the AP. In the example of FIG. **10**, the first packet queue Q**1** may be associated with a first traffic flow (F**1**) intended for STA**1**, the second packet queue Q**2** may be associated with a second traffic flow (F**2**) intended for STA**2**, and the third packet queue Q**3** may be associated with a third traffic flow (F**3**) intended for STA**3**. The traffic flows F**1**-F**3** may be received by the AP from one or more other devices, for example, over a backhaul connection.

[0149] The AP may obtain SLA parameters for each of the traffic flows F**1**-F**3**, network parameters associated with one or more wireless networks (including the BSS operated or managed by the AP), indications of the available space in each of the packet queues Q**1**-Q**3**, or any combination thereof. In some implementations, the SLA parameters obtained by the AP indicate at least a delay bound for each of the traffic flows F**1**-F**3**. For example, the first traffic flow F**1** has a specified delay bound **1001**, the second traffic flow F**2** has a specified delay bound **1002**, and the third traffic flow F**3** has a specified delay bound **1003**. The delay bounds **1001**, **1002**, and **1003** may indicate the maximum amount by which respective traffic flows F**1**-F**3** can be delayed for transmission without violating the latency requirements specified by the SLA parameters. In some instances, the AP may also obtain one or more of the network parameters, the traffic flow attributes, or the SLA parameters for any number of the traffic flows F**1**-F**3**.
[0150] At time t.sub.0, the AP begins receiving and buffering a number of PPDUs **1010** associated with flow F**1** into the first packet queue Q**1**, and continues filling the first packet queue Q**1** with the PPDUs **1010** until time t.sub.2, at which point the amount of data carried by the queued PPDUs **1010** equals or exceeds a first queue data threshold associated with flow F**1**. The first queue data threshold may correspond to the minimum amount of data (Data.sub.min) carried by the queued PPDUs **1010** to enable MU-MIMO communications for flow F**1**. In response thereto, the AP designates the queued PPDUs **1010** of flow F**1** as a candidate for MU-MIMO communications, and delays transmission of the queued PPDUs **1010** by a delay period **1050** that may last until time t.sub.5. During the delay period **1050**, the AP may receive additional packets of flow F**1** and/or other packets associated with other traffic flows.
[0151] While the AP continues receiving the PPDUs **1010** of flow F**1**, the AP begins receiving and buffering a number of PPDUs **1020** associated with flow F**2** into the second packet queue Q**2**, at time t.sub.1. The AP continues filling the second packet queue Q**2** with received PPDUs **1020** until the amount of data carried by the queued PPDUs **1020** equals or exceeds a second queue data threshold associated with flow F**2**, at time t.sub.3. The second queue data threshold may correspond to the minimum amount of data (Data.sub.min) carried by the queued PPDUs **1020** to enable MU-MIMO communications for flow F**2**. In response thereto, the AP designates the queued PPDUs **1020** of flow F**2** as a candidate for MU-MIMO communications, and at time t.sub.3 groups the queued PPDUs **1010** of flow F**1** with the queued PPDUs **1020** of flow F**2** for transmission as an MU-MIMO communication. Specifically, the AP embeds the PPDUs **1010** and **1020** of the first and second traffic flows, respectively, into one or more MU PPDUs, and transmits the one or more MU PPDUs over the wireless medium to STA**1** and STA**2** as an MU-MIMO communication between times t.sub.3-t.sub.4.
[0152] At time t.sub.5, the AP begins receiving and buffering a number of PPDUs **1030** associated with flow F**3** into the third packet queue Q**3**, and continues filling the third packet queue Q**3** with the PPDUs **1030** until time t.sub.6, at which point the amount of data carried by the queued PPDUs **1030** equals or exceeds a third queue data threshold associated with flow F**3**. The third queue data threshold may correspond to the minimum amount of data (Data.sub.min) carried by the queued PPDUs **1030** to enable MU-MIMO communications for flow F**3**. In response thereto, the AP designates the queued PPDUs **1030** of flow F**3** as a candidate for MU-MIMO communications, and delays transmission of the queued PPDUs **1030** by a delay period **1070** that may last until time t.sub.7. During the delay period **1070**, the AP may receive additional packets of flow F**3** and/or other packets associated with other traffic flows. In the example of FIG. **10**, the AP does not receive additional packets prior to expiration of the delay period **1070** at time t.sub.7, and transmits the queued PPDUs **1030** as an SU-MIMO communication over the wireless medium to STA**3** between times t.sub.7-t.sub.8.
[0153] At time t.sub.9, the AP begins receiving and buffering a number of PPDUs **1021** associated with flow F**2** into the second packet queue Q**2**, and continues filling the second packet queue Q**2** with the PPDUs **1021** until time t.sub.11, at which point the amount of data carried by the queued

PPDUs **1021** equals or exceeds the second queue data threshold. In response thereto, the AP designates the queued PPDUs **1021** of flow F**2** as a candidate for MU-MIMO communications, and delays transmission of the queued PPDUs **1021** by a delay period **1061** that may last until time t.sub.15. During the delay period **1061**, the AP may receive additional packets of flow F**2** and/or other packets associated with other traffic flows.

[0154] While the AP continues receiving the PPDUs **1021** of flow F**2**, the AP begins receiving and buffering a number of PPDUs **1011** associated with flow F**1** into the first packet queue Q**1**, at time t.sub.10. The AP continues filling the first packet queue Q**1** with received PPDUs **1011** until the amount of data carried by the queued PPDUs **1011** equals or exceeds the first queue data threshold, at time t.sub.13. In response thereto, the AP designates the queued PPDUs **1011** of flow F**1** as a candidate for MU-MIMO communications, and delays transmission of the queued PPDUs **1011** by a delay period **1051** that may last until time t.sub.15. During the delay period **1051**, the AP may receive additional packets of flow F**1** and/or other packets associated with other traffic flows.

[0155] While the AP receives the PPDUs **1011** of flow F**1** into the first packet queue Q**1**, the AP begins receiving and buffering a number of PPDUs **1031** associated with flow F**3** into the third packet queue Q**3**, at time t.sub.12. The AP continues filling the third packet queue Q**3** with received PPDUs **1031** until the amount of data carried by the queued PPDUs **1031** equals or exceeds the third queue data threshold, at time t.sub.14. In response thereto, the AP designates the queued PPDUs **1031** of flow F**3** as a candidate for MU-MIMO communications, and delays transmission of the queued PPDUs **1031** by a delay period **1071** that may last until time t.sub.15. During the delay period **1071**, the AP may receive additional packets of flow F**3** and/or other packets associated with other traffic flows.

[0156] At time t.sub.15, the delay period **1071** expires at the maximum delay bound **1003** specified by the SLA parameters for flow F**3**. The AP groups the queued PPDUs **1011** of flow F**1**, the queued PPDUs **1021** of flow F**2**, and the queued PPDUs **1031** of flow F**3** for MU-MIMO communications. Specifically, the AP embeds the PPDUs **1011**, the PPDUs **1021**, and the PPDUs **1031** of flows F**1**, F**2**, and F**3**, respectively, into one or more MU PPDUs, and transmits the one or more MU PPDUs over the wireless medium to STA**1**-STA**3** as an MU-MIMO communication between times t.sub.15-t.sub.16.

[0157] At time t.sub.17, the AP begins receiving and buffering a number of PPDUs **1022** associated with flow F**2** into the second packet queue Q**2**, and continues filling the second packet queue Q**2** with the PPDUs **1022** until time t.sub.18, at which point the amount of data carried by the queued PPDUs **1022** equals or exceeds the second queue data threshold. In response thereto, the AP designates the queued PPDUs **1022** of flow F**2** as a candidate for MU-MIMO communications, and delays transmission of the queued PPDUs **1022** by a delay period **1062** that may last until time t.sub.20 or later. During the delay period **1062**, the AP may receive additional packets of flow F**2** and/or other packets associated with other traffic flows.

[0158] After the AP stops receiving and buffering the PPDUs **1022** into the second packet queue Q**2**, the AP begins receiving and buffering a number of PPDUs **1032** associated with flow F**3** into the third packet queue Q**3** at time t.sub.19. The AP continues filling the third packet queue Q**3** with received PPDUs **1032** of flow F**2** during the delay period **1062** until the amount of data carried by the queued PPDUs **1032** equals or exceeds the third queue data threshold, at time t.sub.20. In response thereto, the AP designates the queued PPDUs **1032** of flow F**3** as a candidate for MU-MIMO communications, and groups the queued PPDUs **1022** of flow F**2** with the queued PPDUs **1032** of flow F**3** for MU-MIMO communications. Specifically, the AP embeds the PPDUs **1022** and the PPDUs **1032** into one or more MU PPDUs, and transmits the one or more MU PPDUs over the wireless medium to STA**2** and STA**3** as an MU-MIMO communication between times t.sub.20-t.sub.21.

[0159] FIG. **11** shows a flowchart illustrating an example operation **1100** for wireless communication that supports selectively enabling MU-MIMO communications, according to some implementations. The operation **1100** may be performed by an apparatus such as the wireless communication device **500** described above with reference to FIG. **5**. In some instances, the operation **1100** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively.

[0160] For example, at **1102**, the apparatus obtains one or more packets associated with a traffic flow. At **1104**, the apparatus obtains at least one of one or more SLA parameters associated with the traffic flow, one or more attributes of the traffic flow, or one or more network parameters associated with a basic service set (BSS) that includes the apparatus. At **1106**, the apparatus provides an indication of whether the traffic flow is suitable for transmission over a wireless medium as a single-user (SU) multiple-input multiple output (MIMO) (SU-MIMO) communication, as a multi-user (MU) MIMO (MU-MIMO) communication, as an orthogonal frequency division multiple access (OFDMA) communication, or as a partial bandwidth (BW) SU-MIMO communication, the indication being based on one or more of the SLA parameters, the traffic flow attributes, or the network parameters. At **1108**, the apparatus initiates transmission of the one or more packets over the wireless medium based on the indication.

[0161] In various implementations, the apparatus may include a resource manager configured to obtain the SLA parameters, the traffic flow attributes, and the network parameters based on the slow control loop **702** described with reference to FIG. **7**. In some instances, the resource manager may determine whether the traffic flow is suitable for transmission over the wireless medium via SU-MIMO, MU-MIMO, OFDMA, or partial BW MU-MIMO using one or more of the SLA parameters, the traffic flow attributes, or the network parameters based on the mid control loop **704** described with reference to FIG. **7**. The WLAN subsystem may be configured to transmit traffic flows over the wireless medium based on the transmission modes indicated by the resource manager. In some aspects, the WLAN subsystem may be based on the fast control loop **706** described with reference to FIG. **7**. In some implementations, the fast control loop **702** may be between approximately 1 and 100 milliseconds, the mid control loop **704** may be between approximately 1 and 5 seconds, and the slow control loop **706** may be between approximately 10 and 60 seconds.

[0162] In some implementations, the apparatus may be configured as an access point (AP) associated with the BSS. In some instances, the apparatus may include a transceiver configured to transmit the one or more packets over the wireless medium to one or more STAs associated with the AP. The SLA parameters may include (but are not limited to) one or more of a minimum data rate, a maximum delay bound, a service interval, a burst size, or a throughput requirement for traffic flows associated with the SLA. The network parameters may include (but are not limited to) one or more of interference levels on the wireless medium, a level of channel delay spread associated with the wireless medium, a number of associated wireless stations (STAs) that are active, a number or percentage of the active STAs that support MU-MIMO communications, a number or percentage of the active STAs that support partial BW MU-MIMO communications, a number or percentage of the active STAs that support OFDMA communications, one or more service class parameters, or a traffic load on the wireless medium. The traffic flow attributes may include (but are not limited to) at least a data rate of the traffic flow, an average burst size of the traffic flow, and interarrival times of the one or more packets associated with the traffic flow.

[0163] FIG. **12** shows a flowchart illustrating another example **1200** operation for wireless communication that supports selectively enabling MU-MIMO communications, according to some implementations. The operation **1200** may be performed by an apparatus such as the wireless communication device **500** described above with reference to FIG. **5**. In some implementations, the operation **1200** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively. In some instances, the operation **1200** may be performed after obtaining the parameters at **1104** of FIG. **11**. For example, at **1202**, the apparatus assigns a transmission mode to each packet queue associated with the traffic flow, the transmission mode being one of SU-MIMO, MU-MIMO, OFDMA, or partial BW MU-MIMO based on the indication. In some implementations, the resource manager of the apparatus may indicate the assigned transmission modes to firmware and/or hardware components of the apparatus.

[0164] FIG. **13**A shows a flowchart illustrating another example operation **1300** for wireless communication that supports selectively enabling MU-MIMO communications, according to some implementations. The operation **1300** may be performed by an apparatus such as the wireless communication device **500** described above with reference to FIG. **5**. In some implementations, the operation **1300** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively. In some implementations, the operation **1300** may be performed after obtaining the parameters at **1104** of FIG. **11**. In some instances, the apparatus outputs for transmission the one or more packets as an MU-MIMO transmission based on the traffic flow being associated with latency-sensitive traffic and an amount of payload data carried by the one or more packets being at least equal to a threshold, at **1302**. In other instances, the apparatus outputs for transmission the one or more packets as an OFDMA transmission based on the traffic flow being associated with latency-sensitive traffic and the amount of payload data carried by the one or more packets being less than the threshold, at **1304**.

[0165] FIG. **13**B shows a flowchart illustrating another example operation **1310** for wireless communication that supports selectively enabling MU-MIMO communications, according to some implementations. The operation **1310** may be performed by an apparatus such as the wireless communication device **500** described above with reference to FIG. **5**. In some implementations, the operation **1310** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively. In some implementations, the operation **1310** may be performed after obtaining the parameters at **1104** of FIG. **11**. In some instances, the apparatus outputs for transmission the one or more packets as a partial BW MU-MIMO transmission based on the traffic flow being associated with latency-sensitive traffic and the number of active latency-sensitive traffic flows being at least equal to a threshold number of traffic flows, at **1312**. In other instances, the apparatus outputs for transmission the one or more packets as an MU-MIMO transmission based on the traffic flow not being associated with latency-sensitive traffic and carrying more than a specified amount of data, at **1314**.

[0166] FIG. **13**C shows a flowchart illustrating another example operation **1320** for wireless communication that supports selectively enabling MU-MIMO communications, according to some implementations. The operation **1320** may be performed by an apparatus such as the wireless communication device **500** described above with reference to FIG. **5**. In some implementations, the operation **1320** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively. In some implementations, the operation **1320** may be performed after obtaining the parameters at **1104** of FIG. **11**. In some instances, the apparatus outputs for transmission the one or more packets as an MU-MIMO transmission based at least in part on the maximum delay bound being at least equal to a delay threshold, the throughput requirement being at least equal to a throughput threshold, or both, at **1322**. In other instances, the apparatus outputs for transmission the one or more packets as an OFDMA transmission based at least in part on the maximum delay bound being less than the delay threshold, the throughput requirement being less than the throughput threshold, or both, at **1324**.

[0167] FIG. **13**D shows a flowchart illustrating another example operation **1330** for wireless communication that supports selectively enabling MU-MIMO communications, according to some implementations. The operation **1330** may be performed by an apparatus such as the wireless communication device **500** described above with reference to FIG. **5**. In some implementations, the operation **1330** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively. In some implementations, the operation **1330** may be performed after obtaining the parameters at **1104** of FIG. **11**. In some instances, the apparatus outputs for transmission the one or more packets as an MU-MIMO transmission based at least in part on the interference levels being less than an interference threshold, the channel delay spread being less than a threshold amount, or both, at **1332**. In other instances, the apparatus outputs for transmission the one or more packets as an OFDMA transmission based at least in part on the interference levels being at least equal to the interference threshold, the channel delay spread being at least equal to the threshold amount, or both, at **1334**. In some aspects, the output for transmission as the MU-MIMO transmission may also be based on the number or percentage of active STAs that support MU-MIMO communications being at least equal to a first amount and the number of associated STAs being less than a second amount. In other aspects, the output for transmission as the SU-MIMO or OFDMA transmission may also be based on the number or percentage of active STAs that support MU-MIMO communications being less than the first amount and the number of associated STAs being at least equal to the second amount.

[0168] FIG. **13**E shows a flowchart illustrating another example operation **1340** for wireless communication that supports selectively enabling MU-MIMO communications, according to some implementations. The operation **1340** may be performed by an apparatus such as the wireless communication device **500** described above with reference to FIG. **5**. In some implementations, the operation **1340** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively. In some implementations, the operation **1340** may be performed after obtaining the parameters at **1104** of FIG. **11**. In some instances, the apparatus outputs for transmission the one or more packets as an MU-MIMO transmission based on the respective interarrival times being offset in time from each other by less than a threshold time period and the average burst size being at least equal to a burst size threshold, at **1342**. In other instances, the apparatus outputs for transmission the one or more packets as an SU-MIMO or OFDMA transmission based on the respective interarrival times being offset in time from each other by more than the threshold time period and the average burst size being less than the burst size threshold, at **1344**.

[0169] FIG. **14** shows a flowchart illustrating an example operation **1400** for wireless communication that supports selectively grouping traffic flows for MU-MIMO communications, according to some implementations. The operation **1400** may be performed by a wireless device such as the wireless communication device **500** described above with reference to FIG. **5**. In some instances, the operation **1400** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively.

[0170] For example, at **1402**, the wireless device obtains one or more service-level agreement (SLA) parameters for each traffic flow of a plurality of traffic flows, each traffic flow including a plurality of packets intended for a respective station (STA) of a plurality of STAs associated with the AP, the one or more SLA parameters indicating at least a delay bound for each of the traffic flows. At **1404**, the wireless device receives one or more first packets of a first traffic flow of the plurality of traffic flows. At **1406**, the wireless device delays transmission of the first packets of the first traffic flow for a delay period based at least in part on an amount of data carried in the first packets of the first traffic flow being less than a first threshold. At **1408**, the wireless device receives, during the delay period, one or more second packets of the first traffic flow while also receiving packets of a second traffic flow of the plurality of traffic flows. At **1410**, the wireless device groups, during the delay period, the second traffic flow with the first traffic flow for a multi-user (MU) multiple-input multiple-output (MIMO) transmission based at least in part on an amount of data carried in the first and second packets of the first traffic flow being greater than the first threshold and an amount of data carried in the packets of the second traffic flow being greater than a second threshold. At **1412**, the wireless device transmits, during the delay period, the first and second packets of the first traffic flow with the packets of the second traffic flow as an MU-MIMO communication.

[0171] In various implementations, the one or more SLA parameters may be obtained by a host layer or user space of the AP, and the transmission of the first packets of the first traffic flow may be delayed by a wireless local area network (WLAN) subsystem of the AP. In some implementations, grouping the second traffic flow with the first traffic flow includes selecting the second traffic flow as a candidate for the MU-MIMO transmission based on the amount of data carried in the packets of the second traffic flow exceeding the second threshold prior to expiration of the delay period.

[0172] FIG. **15**A shows a flowchart illustrating another example **1500** operation for wireless communication that supports selectively grouping traffic flows for MU-MIMO communications, according to some implementations. The operation **1500** may be performed by a wireless device such as the wireless communication device **500** described above with reference to FIG. **5**. In some implementations, the operation **1500** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively. In some instances, the operation **1500** may be performed prior to the delay period described with reference to FIG. **14**. For example, at **1502**, the wireless device determines, calculates, or otherwise obtains a load of a basic service set (BSS) associated with the AP. At **1504**, the wireless device adjusts the delay period based on the BSS load. In various implementations, the BSS load may be obtained by a host layer or user space of the wireless device, and the delay period may be adjusted by a wireless local area network (WLAN) subsystem of the wireless device based on an indication provided by the host layer or user space.

[0173] In some implementations, the adjusted delay period is between zero and the delay bound for the first traffic flow. In some instances, the wireless device increases the delay period based on the BSS load being less than a value. In other instances, the wireless device decreases the delay period based on the BSS load being greater than the value. In some other instances, the wireless device sets the delay period to zero based on the BSS load being greater than a configured amount. As discussed, setting the delay period to zero prevents delaying the transmission of queued packets associated with the first traffic flow for possible MU-MIMO grouping with one or more other traffic flows. In some aspects, the wireless device may transmit the queued packets associated with the first traffic flow as an OFDMA communication. In other aspects, the wireless device may transmit the queued packets associated with the first traffic flow as an SU-MIMO communication.

[0174] FIG. **15**B shows a flowchart illustrating another example **1510** operation for wireless communication that supports selectively grouping traffic flows for MU-MIMO communications, according to some implementations. The operation **1510** may be performed by a wireless device such as the wireless communication device **500** described above with reference to FIG. **5**. In some implementations, the operation **1510** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively. In some instances, the operation **1510** may be performed prior to the delay period described with reference to FIG. **14**. For example, at **1512**, the wireless device determines, calculates, or otherwise obtains a load of a basic service set (BSS) associated with the AP. At **1514**, the wireless device adjusts one or both of the first and second thresholds based on the BSS load.

[0175] In various implementations, the BSS load may be determined, calculated, or otherwise obtained by a host layer or user space of the wireless device, and the delay period may be adjusted by a WLAN subsystem of the wireless device based on an indication provided by the host layer or user space. In some instances, the wireless device may decrease one or both of the first and second thresholds based on the BSS load being less than a value. In other instances, the wireless device may increase one or both of the first and second thresholds based on the BSS load being greater than the value.

[0176] FIG. **15**C shows a flowchart illustrating another example **1520** operation for wireless communication that supports selectively grouping traffic flows for MU-MIMO communications, according to some implementations. The operation **1520** may be performed by a wireless device such as the wireless communication device **500** described above with reference to FIG. **5**. In some implementations, the operation **1520** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively. In some instances, the operation **1520** may be performed prior to the delay period described with reference to FIG. **14**. For example, at **1522**, the wireless device obtains respective indications of available space in one or more buffers within which received packets of the first and second traffic flows are queued. At **1524**, the wireless device adjusts one or both of the first and second thresholds based on the indicated available space.

[0177] In various implementations, the indications of available space in the one or more buffers may be determined, calculated, or otherwise obtained by a host layer or user space of the wireless device, and the delay period may be adjusted by a WLAN subsystem of the wireless device based on an indication provided by the host layer or user space. In some instances, the wireless device may decrease one or both of the first and second thresholds based on the indicated available space being less than a value. In other instances, the wireless device may increase one or both of the first and second thresholds based on the indicated available space being greater than the value.

[0178] FIG. **15**D shows a flowchart illustrating another example **1530** operation for wireless communication that supports selectively grouping traffic flows for MU-MIMO communications, according to some implementations. The operation **1530** may be performed by a wireless device such as the wireless communication device **500** described above with reference to FIG. **5**. In some implementations, the operation **1530** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively. In some instances, the operation **1530** may be performed prior to the delay period described with reference to FIG. **14**. For example, at **1532**, the wireless device obtains a traffic type of the first traffic flow. At **1534**, the wireless device decreases the delay period based on the obtained traffic type being a Transmission Control Protocol (TCP) traffic type. In some other implementations, the wireless device may disable UL MU trigger frames for TCP traffic and/or other bidirectional traffic when UL traffic is transmitted using UL SU communications. In this way, aspects of the present disclosure may ensure that UL MU trigger frames do not unnecessarily consume the AP's channel access for delivery of DL TCP traffic.

[0179] FIG. **16**A shows a flowchart illustrating another example **1600** operation for wireless communication that supports selectively grouping traffic flows for MU-MIMO communications, according to some implementations. The operation **1600** may be performed by a wireless device such as the wireless communication device **500** described above with reference to FIG. **5**. In some implementations, the operation **1600** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively. In some instances, the operation **1600** may be performed during the delay period described with reference to FIG. **14**. For example, at **1602**, the wireless device receives packets of a third traffic flow during the delay period. At **1604**, the wireless device groups the third traffic flow with the first and second traffic flows for the MU-MIMO transmission based at least in part on an amount of data carried in the packets of the third traffic flow being greater than a third threshold. In some implementations, the packets of the third traffic flow are transmitted with the packets of the first and second traffic flows as the MU-MIMO communication.

[0180] FIG. **16**B shows a flowchart illustrating another example **1610** operation for wireless communication that supports selectively grouping traffic flows for MU-MIMO communications, according to some implementations. The operation **1610** may be performed by a wireless device such as the wireless communication device **500** described above with reference to FIG. **5**. In some implementations, the operation **1610** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively. In some instances, the operation **1610** may be performed prior to the delay period described with reference to FIG. **14**. For example, at **1612**, the wireless device adjusts at least one of the first threshold, the second threshold, or the delay period based on one or more of the number of traffic flows that are eligible for grouping in the MU-MIMO transmission, an average data rate of the STAs for which the eligible traffic flows are intended, an average amount of data received by the STAs for which the eligible traffic flows are intended, channel conditions of a wireless medium associated with the AP, a level of contention on the wireless medium, a level of interference on the wireless medium, or a channel occupancy of the wireless medium.

[0181] FIG. **16**C shows a flowchart illustrating another example **1620** operation for wireless communication that supports selectively grouping traffic flows for MU-MIMO communications, according to some implementations. The operation **1620** may be performed by a wireless device such as the wireless communication device **500** described above with reference to FIG. **5**. In some implementations, the operation **1620** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively. In various aspects, the operation **1620** may be performed prior to the delay period described with reference to FIG. **14**.

[0182] In some instances, the wireless device adjusts the delay period based on the minimum data rate for the first traffic flow being greater than a first value, at **1622**. In other instances, the wireless device sets the delay period to zero based on the minimum data rate for the first traffic flow being less than a second value, the second value being less than the first value, at **1624**. As discussed, setting the delay period to zero prevents delaying the transmission of queued packets associated with the first traffic flow for possible MU-MIMO grouping with one or more other traffic flows. In some aspects, the wireless device may transmit the queued packets associated with the first traffic flow as an OFDMA communication. In other aspects, the wireless device may transmit the queued packets associated with the first traffic flow as an SU-MIMO communication.

[0183] FIG. **16**D shows a flowchart illustrating another example **1630** operation for wireless communication that supports selectively grouping traffic flows for MU-MIMO communications, according to some implementations. The operation **1630** may be performed by a wireless device such as the wireless communication device **500** described above with reference to FIG. **5**. In some implementations, the operation **1630** may be performed by a wireless device operating as or within an AP, such as one of the APs **102**, **602**, or **720** described above with reference to FIGS. **1**, **6**A, and **7**, respectively.

[0184] In various aspects, the operation **1630** may be performed after the operation **1400** described with reference to FIG. **14**. For example, at **1632**, the wireless device obtains feedback information indicating that at least a number or percentage of the plurality of traffic flows are not grouped with one another for MU-MIMO transmissions prior to expiration of the respective delay periods of the number or percentage of traffic flows. At **1634**, the wireless device adjusts one or more of the respective delay period, the respective first threshold, or the respective second threshold associated with each traffic flow of the number or percentage of traffic flows based on the feedback information.

[0185] FIG. **17** is a conceptual data flow diagram **1700** illustrating the data flow between different means and/or components of an example apparatus **1702**. In some implementations, the apparatus **1702** may be implemented within an AP. In some other implementations, the apparatus **1702** may be a wireless device that operates as a STA associated with a WLAN while also operating as a softAP associated with one or more client devices (not shown for simplicity). The apparatus **1702** includes a reception component **1704** that receives data packets from another wireless device **1750**. In some aspects, the reception component **1704** may also receive or obtain feedback information from one or more wireless networks, traffic flow attributes of the traffic flows communicated over at least some of the one or more wireless networks, and SLA parameters associated with the traffic flows. The apparatus **1702** also includes a resource manager **1706**, a kernel **1708**, a firmware component **1710**, a hardware component **1712**, and a transmission component **1714**.

[0186] The resource manager **1706** may determine whether or not to enable MU communications for each traffic flow received by the apparatus **1702** based on one or more SLA parameters, one or more traffic flow attributes, one or more network parameters of the BSS that includes the apparatus **1702**, one or more network parameters of other BSSs, or any combination thereof. In some aspects, at least some of the traffic flow attributes and network parameters may be provided by an operator cloud based on the slow control loop **706** described with reference to FIG. **7**. In some implementations, the resource manager **1706** may provide an indication of whether each traffic flow is suitable for transmission over the wireless medium as an SU-MIMO communication, as an MU-MIMO communication, as an OFDMA communication, or as a partial BW MU-MIMO communication based on one or more of the SLA parameters, the traffic flow attributes, or the network parameters. In some aspects, the resource manager **1706** may provide the indication to the firmware component **1710** based on the mid control loop **704** described with reference to FIG. **7**. The kernel **1708** may facilitate interactions between hardware and software components of the apparatus **1702**. The firmware component **1710** may schedule transmissions of the traffic flows based on the indications provided by the resource manager **1706**. In some aspects, the firmware component **1710** may indicate whether the hardware component **1712** is to group queued packets associated with different traffic flows for concurrent transmission over the wireless medium using MU-MIMO, OFDMA, or partial BW MU-MIMO. The hardware component **1712** may include processing and communication cores that control various aspects of the transmission component **1714**. In some aspects, the hardware component **1712** may be based on the fast control loop **702** described with reference to FIG. **7**.

[0187] The transmission component **1714** is coupled to the resource manager **1706** and the hardware component **1712**, may be used to transmit frames or packets provided by the hardware component **1712** to other wireless communication devices. The transmission component **1714** may include PHY components, such as transceivers, which are responsible for transmitting packets of the traffic flows over the wireless medium to their intended receiving devices. In some instances, the transmission component **1714** may concurrently transmit multiple traffic flows over the wireless medium based on MU-MIMO, OFDMA, or partial BW MU-MIMO. In other instances, the transmission component **1714** may transmit traffic flows over the wireless medium based on SU-MIMO.

[0188] The apparatus **1702** may include additional components that perform each of the blocks of the operations described with reference to FIGS. **11**, **12**, and **13**A-**13**D. As such, each block in the flowcharts of FIGS. **11**, **12**, and **13**A-**13**D may be performed by a component, and the apparatus **1702** may include one or more of those components. The components may be one or more hardware components specifically configured to carry out the stated processes/algorithm, implemented by a processor configured to perform the stated processes/algorithm, stored within a computer-readable medium for implementation by a processor, or some combination thereof.

[0189] FIG. **18** is a diagram **1800** illustrating an example of a hardware implementation for an apparatus **1702**′ employing a processing system **1814**. The processing system **1814** may be implemented with a bus architecture, represented generally by the bus **1824**. The bus **1824** may include any number of interconnecting buses and bridges depending on the specific application of the processing system **1814** and the overall design constraints. The bus **1824** links together various circuits including one or more processors and/or hardware components, represented by the processor **1804**, the components **1704**, **1706**, **1708**, **1710**, **1712**, and **1714**, and the computer-readable medium/memory **1806**. The bus **1824** may also link various other circuits such as timing sources, peripherals, voltage regulators, and power management circuits, which are well known in the art, and therefore, will not be described any further.

[0190] The processing system **1814** may be coupled to a transceiver **1810**. The transceiver **1810** is coupled to one or more antennas **1820**. The transceiver **1810** provides a means for communicating with various other apparatus over a transmission medium. The transceiver **1810** receives a signal from the one or more antennas **1820**, extracts information from the received signal, and provides the extracted information to the processing system **1814**, specifically the reception component **1704**. In addition, the transceiver **1810** receives information from the processing system **1814**, specifically the transmission component **1714**, and based on the received information, generates a signal to be applied to the one or more antennas **1820**. The processing system **1814** includes a processor **1804** coupled to a computer-readable medium/memory **1806**. The processor **1804** is responsible for general processing, including the execution of software stored on the computer-readable medium/memory **1806**. The software, when executed by the processor **1804**, causes the processing system **1814** to perform the various functions described supra for any particular apparatus. The computer-readable medium/memory **1806** may also be used for storing data that is manipulated by the processor **1804** when executing software. The processing system **1814** further includes at least one of the components **1704**, **1706**, **1708**, **1710**, and **1712**. The components may be software components running in the processor **1804**, resident/stored in the computer readable medium/memory **1806**, one or more hardware components coupled to the processor **1804**, or some combination thereof.
[0191] In certain configurations, the apparatus **1702**/**1702′** for wireless communication may include means for all means limitations described herein. The aforementioned means may be the modem **502**, the radio **504**, the processor(s) **506**, the memory **508**, and one or more of the aforementioned components of the apparatus **1702** and/or the processing system **1814** of the apparatus **1702′** configured to perform the functions recited by the aforementioned means.
[0192] In one configuration, the apparatus **1802**/**1802′** for wireless communication includes means for obtaining one or more packets associated with a traffic flow, means for obtaining at least one of one or more SLA parameters associated with the traffic flow, one or more attributes of the traffic flow, or one or more network parameters associated with a BSS that includes the apparatus, means for providing indication of whether the traffic flow is suitable for transmission over a wireless medium as an SU-MIMO communication, as an MU-MIMO communication, as an OFDMA communication, or as a partial bandwidth BW MU-MIMO communication based on one or more of the SLA parameters, the traffic flow attributes, or the network parameters. The apparatus **1702**/**1702′** for wireless communication also includes means for initiating transmission of the one or more packets over the wireless medium based on the indication. The aforementioned means may be one or more of the aforementioned components of the apparatus **1802** and/or the processing system **1814** of the apparatus **1702′** configured to perform the functions recited by the aforementioned means. As described supra, the processing system **1814** may include modem **502**, the radio **504**, the processor(s) **506**, the memory **508** of FIG. **5**.
Example Aspects
[0193] Aspect 1: A method for wireless communication at an access point (AP), including: obtaining one or more packets associated with a traffic flow; obtaining at least one of one or more service-level agreement (SLA) parameters associated with the traffic flow, one or more attributes of the traffic flow, or one or more network parameters associated with a basic service set (BSS) that includes the AP; providing an indication of whether the traffic flow is suitable for transmission over a wireless medium as a single-user (SU) multiple-input multiple output (MIMO) (SU-MIMO) communication, as a multi-user (MU) MIMO (MU-MIMO) communication, as an orthogonal frequency division multiple access (OFDMA) communication, or as an MU-OFDMA communication, the indication being based on one or more of the SLA parameters, the traffic flow attributes, or the network parameters; and initiating transmission of the one or more packets over the wireless medium based on the indication. [0194] Aspect 2: The method of aspect 1, further including: assigning a transmission mode to each packet queue associated with the traffic flow, the

transmission mode being one of SU-MIMO, MU-MIMO, OFDMA, or partial BW MU-MIMO based on the indication. [0195] Aspect 3: The method of any of aspects 1-2, further including: selecting a transmission mode for the WLAN subsystem based on the indication. [0196] Aspect 4: The method of any of aspects 1-3, further including: outputting for transmission the one or more packets as an MU-MIMO transmission based on the traffic flow being associated with latency-sensitive traffic and an amount of payload data carried by the one or more packets being at least equal to a threshold; or outputting for transmission the one or more packets as an OFDMA transmission based on the traffic flow being associated with latency-sensitive traffic and the amount of payload data carried by the one or more packets being less than the threshold. [0197] Aspect 5: The method of any of aspects 1-4, further including: outputting for transmission the one or more packets as an MU-OFDMA transmission based on the traffic flow being associated with latency-sensitive traffic and the number of active latency-sensitive traffic flows being at least equal to a threshold number of traffic flows; or outputting for transmission the one or more packets as an MU-MIMO transmission based on the traffic flow not being associated with latency-sensitive traffic and carrying more than a specified amount of data. [0198] Aspect 6: The method of any of aspects 1-5, wherein the SLA parameters include one or more of a minimum data rate, a maximum delay bound, a service interval, a burst size, or a throughput requirement for traffic flows associated with the SLA. [0199] Aspect 7: The method of any of aspects 1-6, further including outputting for transmission the one or more packets as an MU-MIMO transmission based at least in part on the maximum delay bound being at least equal to a delay threshold, the throughput requirement being at least equal to a throughput threshold, or both; or outputting for transmission the one or more packets as an OFDMA transmission based at least in part on the maximum delay bound being less than the delay threshold, the throughput requirement being less than the throughput threshold, or both. [0200] Aspect 8: The method of aspect 7, wherein: outputting the one or more packets for transmission as the MU-MIMO transmission is further based on the minimum data rate being at least equal to a data rate threshold; or outputting the one or more packets for transmission as the OFDMA transmission is further based on the minimum data rate being less than the data rate threshold. [0201] Aspect 9: The method of any of aspects 1-8, wherein the network parameters include one or more of interference levels on the wireless medium, a level of channel delay spread associated with the wireless medium, a number of associated wireless stations (STAs) that are active, a number or percentage of the active STAs that support MU-MIMO communications, a number or percentage of the active STAs that support partial BW MU-MIMO communications, a number or percentage of the active STAs that support OFDMA communications, one or more service class parameters, or a traffic load on the wireless medium. [0202] Aspect 10: The method of aspect 9, further including: outputting for transmission the one or more packets as an MU-MIMO transmission based at least in part on the interference levels being less than an interference threshold, the level of channel delay spread being less than a threshold amount, or both; or outputting for transmission the one or more packets as an OFDMA transmission based at least in part on the interference levels being at least equal to the interference threshold, the level of channel delay spread being at least equal to the threshold amount, or both. [0203] Aspect 11: The method of aspect 10, wherein: outputting the one or more packets for transmission as the MU-MIMO transmission is further based on the number or percentage of active STAs that support MU-MIMO communications being at least equal to a first amount and the number of active STAs being less than a second amount; or outputting the one or more packets for transmission as the SU-MIMO or OFDMA transmission is further based on the number or percentage of active STAs that support MU-MIMO communications being less than the first amount and the number of associated STAs being at least equal to the second amount. [0204] Aspect 12: The method of any of aspects 1-11, wherein the traffic flow attributes include one or more of a data rate of the traffic flow, an average burst size of the traffic flow, or interarrival times of the one or more packets associated with the traffic flow. [0205] Aspect 13: The method of aspect 12, further including: outputting for transmission the one or more packets as an MU-MIMO transmission based on the respective interarrival times being offset in time from each other by less than a threshold time period and the average burst size being greater than a burst size threshold; or outputting for transmission the one or more packets as an SU-MIMO or OFDMA transmission based on the respective interarrival times being offset in time from each other by more than the threshold time period and the average burst size being less than the burst size threshold. [0206] Aspect 14: The method of aspect 13, wherein: outputting the one or more packets for transmission as the MU-MIMO transmission is further based on the data rate being at least equal to a data rate threshold; or outputting the one or more packets for transmission as the SU-MIMO or OFDMA transmission is further based on the data rate being less than the data rate threshold. [0207] Aspect 15: The method of any of aspects 1-14, further including implementing a first timing loop and a second timing loop, the first timing loop being between approximately 1 and 100 milliseconds, the second timing loop being between approximately 1 and 5 seconds. [0208] Aspect 16: The method of aspect 15, further including obtaining the network parameters and the traffic flow attributes from an external source based on a third timing loop, the third timing loop being between approximately 10 and 60 seconds. [0209] Aspect 17: An access point (AP), including: at least one transceiver; a memory including instructions; and one or more processors configured to execute the instructions and cause the AP to perform a method in accordance with any one of Aspects 1-16, wherein the at least one transceiver is configured to receive one or more packets associated with a traffic flow and to transmit the one or more packets over a wireless medium. [0210] Aspect 18: An apparatus for wireless communications, including means for performing a method in accordance with any one of Aspects 1-16. [0211] Aspect 19: A non-transitory computer-readable storage medium storing instructions that, when executed by one or more processors of an apparatus, cause the apparatus to perform one or more operations in accordance with any one of Aspects 1-16.

[0212] As used herein, a phrase referring to “at least one of” or “one or more of” a list of items refers to any combination of those items, including single members. For example, “at least one of: a, b, or c” is intended to cover the possibilities of: a only, b only, c only, a combination of a and b, a combination of a and c, a combination of b and c, and a combination of a and b and c. As used herein, “based on” is intended to be interpreted in the inclusive sense, unless otherwise explicitly indicated. For example, “based on” may be used interchangeably with “based at least in part on,” unless otherwise explicitly indicated. Specifically, unless a phrase refers to “based on only ‘a,’” or the equivalent in context, whatever it is that is “based on ‘a,’” or “based at least in part on ‘a,’” may be based on “a” alone or based on a combination of “a” and one or more other factors, conditions or information.

[0213] The various illustrative components, logic, logical blocks, modules, circuits, operations and algorithm processes described in connection with the implementations disclosed herein may be implemented as electronic hardware, firmware, software, or combinations of hardware, firmware or software, including the structures disclosed in this specification and the structural equivalents thereof. The interchangeability of hardware, firmware and software has been described generally, in terms of functionality, and illustrated in the various illustrative components, blocks, modules, circuits and processes described above. Whether such functionality is implemented in hardware, firmware or software depends upon the particular application and design constraints imposed on the overall system.

[0214] Various modifications to the implementations described in this disclosure may be readily apparent to persons having ordinary skill in the art, and the generic principles defined herein may be applied to other implementations without departing from the spirit or scope of this disclosure. Thus, the claims are not intended to be limited to the implementations shown herein, but are to be accorded the widest scope consistent with this disclosure, the principles and the novel features disclosed herein.

[0215] Additionally, various features that are described in this specification in the context of separate implementations also can be implemented in combination in a single implementation. Conversely, various features that are described in the context of a single implementation also can be implemented in multiple implementations separately or in any suitable subcombination. As such, although features may be described above as acting in particular combinations, and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination.

[0216] Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. Further, the drawings may schematically depict one more example processes in the form of a flowchart or flow diagram. However, other operations that are not depicted can be incorporated in the example processes that are schematically illustrated. For example, one or more additional operations can be performed before, after, simultaneously, or between any of the illustrated operations. In some circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the implementations described above should not be understood as requiring such separation in all implementations, and it should be understood that the described program components and systems can generally be integrated together in a single software product or packaged into multiple software products.

Claims

1. (canceled)

2. An apparatus for wireless communications, comprising: a processing system that comprises one or more processors and memory that stores instructions, wherein the processing system is configured to cause the apparatus to: obtain one or more service-level agreement (SLA) parameters of a traffic flow, one or more attributes of the traffic flow, and one or more network parameters of a basic service set (BSS) that comprises the apparatus; provide an indication of whether the traffic flow is suitable for transmission over a wireless medium via one or more transmission modes comprising single-user (SU) multiple-input multiple output (MIMO) (SU-MIMO) communications, multi-user (MU) MIMO (MU-MIMO) communications, orthogonal frequency division multiple access (OFDMA) communications, or partial bandwidth (BW) MU-MIMO communications, the indication being based at least in part on the one or more SLA parameters of the traffic flow, the one or more attributes of the traffic flow, and the one or more network parameters of the BSS; and initiate transmission of one or more packets of the traffic flow over the wireless medium in accordance with a transmission mode of the one or more transmission modes based at least in part on the indication.

3. The apparatus of claim 2, wherein a resource manager of the apparatus provides the indication to a wireless local area network (WLAN) subsystem of the apparatus, and wherein the resource manager implements a first timing loop and the WLAN subsystem implements a second timing loop.

4. The apparatus of claim 3, wherein the resource manager: obtains the one or more SLA parameters based at least in part on the first timing loop, provides the indication to the WLAN subsystem based at least in part on the second timing loop, and obtains the one or more network parameters and the one or more attributes of the traffic flow from one or more external sources based at least in part on a third timing loop.

5. The apparatus of claim 4, wherein the first timing loop is between approximately 1 and 100 milliseconds, wherein the second timing loop is between approximately 1 and 5 seconds, and wherein the third timing loop is between approximately 10 and 60 seconds.

6. The apparatus of claim 2, wherein the processing system is further configured to cause the apparatus to: assign a respective transmission mode to each packet queue associated with the traffic flow, the transmission mode being one of SU-MIMO, MU-MIMO, OFDMA, or partial BW MU-MIMO based at least in part on the indication.

7. The apparatus of claim 2, wherein the one or more network parameters comprise one or more of one or more interference levels on the wireless medium, a level of channel delay spread of the wireless medium, a quantity of associated wireless stations (STAs) that are active, a quantity or percentage of the associated wireless STAs that are active that support MU-MIMO communications, a quantity or percentage of the associated wireless STAs that are active that support partial BW MU-MIMO communications, a quantity or percentage of the associated wireless STAs that are active that support OFDMA communications, one or more service class parameters, or a traffic load on the wireless medium.

8. The apparatus of claim 7, wherein the processing system is further configured to cause the apparatus to: output the one or more packets for transmission as a MU-MIMO transmission based at least in part on the quantity or percentage of the associated wireless STAs that are active that support the MU-MIMO communications being at least equal to a first amount and the quantity of the associated wireless STAs that are active being less than a second amount; or output the one or more packets for transmission as an OFDMA transmission based at least in part on the quantity or percentage of the associated wireless STAs that are active that support the MU-MIMO communications being less than the first amount and the quantity of the associated wireless STAs that are active being at least equal to the second amount.

9. The apparatus of claim 2, wherein the processing system is further configured to cause the apparatus to: output, for transmission, the one or more packets as a partial BW MU-MIMO transmission based at least in part on a latency tolerance of the one or more packets, on a quantity of active latency-sensitive traffic flows being at least equal to a threshold quantity of traffic flows, or both.

10. The apparatus of claim 2, wherein the processing system is further configured to cause the apparatus to: output, for transmission, the one or more packets as a MU-MIMO transmission or an OFDMA transmission based at least in part on interference levels on the wireless medium, a level of channel delay spread of the wireless medium, or both.

11. The apparatus of claim 2, wherein the processing system is further configured to cause the apparatus to: output, for transmission, the one or more packets as a MU-MIMO transmission based at least in part on the traffic flow comprising latency-sensitive traffic and an amount of payload data carried by the one or more packets being at least equal to a threshold; or output, for transmission, the one or more packets as a OFDMA transmission based at least in part on the traffic flow comprising latency-sensitive traffic and the amount of payload data carried by the one or more packets being less than the threshold.

12. The apparatus of claim 2, wherein the one or more SLA parameters comprise one or more of a minimum data rate, a maximum delay bound, a service interval, a target throughput, or a burst size for traffic flows having an SLA.

13. The apparatus of claim 12, w herein the processing system is further configured to cause the apparatus to: output, for transmission, the one or more packets as a MU-MIMO transmission based at least in part on a maximum delay bound being at least equal to a delay threshold, on the target throughput of the one or more packets being at least equal to a throughput threshold, on the minimum data rate being at least equal to a data rate threshold, or any combination thereof; or output, for transmission, the one or more packets as a OFDMA transmission based at least in part on the maximum delay bound being less than the delay threshold, the target throughput of the one or more packets being less than the throughput threshold, on the minimum data rate being less than the data rate threshold, or any combination thereof.

14. The apparatus of claim 12, wherein the processing system is further configured to cause the apparatus to: output, for transmission, the one or more packets as a MU-MIMO transmission or a

SU-MIMO transmission based at least in part on respective interarrival times of the one or more packets of the traffic flow and an average burst size of the traffic flow being.

15. The apparatus of claim 12, wherein the one or more attributes of the traffic flow comprise one or more of a data rate of the traffic flow, an average burst size of the traffic flow, or respective interarrival times of the one or more packets of the traffic flow.

16. A method for wireless communications at an access point (AP), comprising: obtaining one or more service-level agreement (SLA) parameters of a traffic flow, one or more attributes of the traffic flow, and one or more network parameters of a basic service set (BSS) that comprises the AP; providing an indication of whether the traffic flow is suitable for transmission over a wireless medium via one or more transmission modes comprising single-user (SU) multiple-input multiple output (MIMO) (SU-MIMO) communications, multi-user (MU) MIMO (MU-MIMO) communications, orthogonal frequency division multiple access (OFDMA) communications, or partial bandwidth (BW) MU-MIMO communications, the indication being based at least in part on the one or more SLA parameters of the traffic flow, the one or more attributes of the traffic flow, and the one or more network parameters of the BSS; and initiating transmission of one or more packets of the traffic flow over the wireless medium in accordance with a transmission mode of the one or more transmission modes based at least in part on the indication.

17. The method of claim 16, wherein a resource manager of the AP provides the indication to a wireless local area network (WLAN) subsystem of the AP, wherein the resource manager implements a first timing loop and the WLAN subsystem implements a second timing loop.

18. The method of claim 17, wherein the resource manager: obtains the one or more SLA parameters based at least in part on the first timing loop, provides the indication to the WLAN subsystem based at least in part on the second timing loop, and obtains the one or more network parameters and the one or more attributes of the traffic flow from one or more external sources based at least in part on a third timing loop.

19. The method of claim 18, wherein the first timing loop is between approximately 1 and 100 milliseconds, wherein the second timing loop is between approximately 1 and 5 seconds, and wherein the third timing loop is between approximately 10 and 60 seconds.

20. The method of claim 16, further comprising: assigning a respective transmission mode to each packet queue associated with the traffic flow, the transmission mode being one of SU-MIMO, MU-MIMO, OFDMA, or partial BW MU-MIMO based at least in part on the indication.

21. A non-transitory computer-readable medium storing code for wireless communications at an access point (AP), the code comprising instructions executable by one or more processors to: obtain one or more service-level agreement (SLA) parameters of a traffic flow, one or more attributes of the traffic flow, and one or more network parameters of a basic service set (BSS) that comprises the AP; provide an indication of whether the traffic flow is suitable for transmission over a wireless medium via one or more transmission modes comprising single-user (SU) multiple-input multiple output (MIMO) (SU-MIMO) communications, multi-user (MU) MIMO (MU-MIMO) communications, orthogonal frequency division multiple access (OFDMA) communications, or partial bandwidth (BW) MU-MIMO communications, the indication being based at least in part on the one or more SLA parameters of the traffic flow, the one or more attributes of the traffic flow, and the one or more network parameters of the BSS; and initiate transmission of one or more packets of the traffic flow over the wireless medium in accordance with a transmission mode of the one or more transmission modes based at least in part on the indication.