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Adaptive point-to-point communication approach for subscriber stations in broadband wireless networks

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Abstract The point-to-multipoint (PMP) mode is considered the well-adopted transmission type that is supported by the IEEE 802.16 standard. The base station (BS) is served as the centralized coordinator to control and forward packets for the subscriber stations (SSs) within the network. In the case that two SSs intend to conduct packet transmission, it is required for the packets to be rerouted to the BS before arriving at the destination SS. The communication bandwidth is apparently wasted due to the rerouting processes. In this paper, an adaptive point-to-point communication (APC) approach is proposed to achieve direct communication between SSs within the PMP mode of the IEEE 802.16 standard. The BS is coordinating and arranging specific time intervals for the two SSs that are actively involved in packet transmission. Based on channel conditions among the BS and the SSs, the packet transmission operation is switched between direct communication and indirect communication in the APC approach. Both the architectural design and analytical modeling of the proposed scheme are conducted in this paper. The effectiveness of the proposed APC approach in terms of user throughput and its corresponding overhead can be observed via both the analytical and simulation results.

Keywords IEEE 802.16 · Broadband wireless access · Medium access control · Point-to-point communications · Protocol design and analysis · Performance analysis

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1 Introduction

The IEEE 802.16 standard for wireless metropolitan area networks (WMANs) is designed to satisfy various demands for higher capacity, higher data rate, and more advanced multimedia services [1–8]. The medium access control (MAC) layer of IEEE 802.16 networks supports both mesh and point-to-multipoint (PMP) modes for packet transmission [1]. Based on the application requirements, it is suggested in the standard that only one of the modes can be exploited by the network components within considered time intervals. In the mesh mode, communication can occur directly between subscriber stations (SSs) with potential packet-rerouting via other SSs. On the other hand, packet transmission is coordinated by the base station (BS) in the PMP mode. The BS is responsible for controlling the communication with multiples SSs in both downlink (DL) and uplink (UL) directions. It has been recommended in the standard that the PMP mode should be utilized in most of the communication scenarios. However, the inefficiency within the PMP mode occurs while two SSs are intended to conduct packet transmission, e.g., file sharing or video conferencing conducted by adjacent buildings. It is required for the data packets between the SSs to be forwarded by the BS even though the SSs are adjacent with each others. Due to the packet rerouting process, the communication bandwidth is wasted which consequently increases control overhead and packet-rerouting delay.

In order to alleviate the drawbacks resulting from the indirect transmission, a directly communicable algorithm between SSs should be considered in IEEE 802.16 networks. Several direct communication approaches have been proposed for different types of networks. The direct-link setup (DLS) protocol is standardized in the IEEE 802.11z draft standard to support direct communication between two SSs in wireless local networks [9]. However, the DLS protocol is designed as a contention-based mechanism, which does not guarantee the access of direct link setup and data exchanges between two SSs. The dynamic slot assignment (DSA) scheme for Bluetooth networks is proposed in [10, 11], which is primarily implemented based on the characteristics of the Bluetooth standard [12]. Since frame structures and medium access mechanisms are different among these wireless communication technologies, both the DLS protocol and DSA scheme cannot be directly applied to IEEE 802.16 networks. For the IEEE 802.16 PMP networks, the virtual direct link access (VDLA) mechanism is proposed in [13], which partially overlaps the DL and UL subframes within a single frame. The source SS and destination SS are scheduled in the overlapped time intervals in order to accomplish the direct transmission. However, since channel conditions among the BS and the two SSs can be different, it will not always attainable to assume that both the source and destination SSs process the common burst profile in the VDLA scheme.

In this paper, a flexible and contention-free approach, named adaptive point-to-point communication (APC), is proposed to support direct communication for SSs in IEEE 802.16 PMP networks. The complete data structures and procedures for implementing direct communication are proposed. According to channel conditions among the BS and SSs, the packet transmission operation is automatically switched between the direct link and indirect links, which results in enhanced network throughput. While the direct link approach is selected, the required bandwidth, communication overhead, and packet latency can be greatly reduced. The effectiveness of the APC approach is evaluated and validated via both the numerical analysis and extensive simulation studies. It can be shown that the proposed APC approach outperforms the conventional IEEE 802.16 transmission mechanism in terms of user throughput, communication overhead, and packet latency. In summary, the contributions of this paper are listed as follows: (a) the proposal of a comprehensive architectural design associated with the extended frame structures for conducting direct communication; (b) an adaptive communication approach that can dynamically select the most efficient packet transmission scheme between the direct and indirect communication; (c) an approach that is fully compatible and can be directly integrated with the existing protocols defined in the IEEE 802.16 standard; and (d) numerical analysis and extensive simulations to justify the effectiveness of the proposed scheme.

The rest of this paper is organized as follows. Section 2 briefly reviews the frame structures and the packet transmission mechanism in the IEEE 802.16 PMP mode. The proposed APC approach is described in Sect. 3; while the numerical analysis is carried in Sect. 4. Both the performance evaluation and validation of the APC approach are conducted in Sect. 5. Section 6 draws the conclusions.

2 IEEE 802.16 PMP networks

The PMP mode is considered the well-adopted network configuration in IEEE 802.16 networks wherein the BS is responsible for controlling all the communication among SSs. Two duplexing techniques are supported for the SSs to share common channels, i.e., time division duplexing (TDD) and frequency division duplexing. The MAC protocol is structured to support multiple physical (PHY) layer specifications in the IEEE 802.16 standard. In this paper, the WirelessMAN-OFDM PHY, utilizing the orthogonal frequency division multiplexing (OFDM), with TDD scheme is exploited for the design of the proposed APC approach. The OFDM is considered a promising air interface for supporting non-line of sight operations in fixed broadband wireless access networks [14]; while the TDD mode is extensively adopted in both the licensed and licensed-exempt bands that are specified in most of the existing commercial IEEE 802.16 devices.

2.1 Frame structure

Figure 1 illustrates the schematic diagram of the IEEE 802.16 PMP OFDM frame structure with TDD mode. It can be observed that each frame consists of a DL subframe and a UL subframe. Each DL subframe contains only one DL PHY protocol data unit (PDU), which starts with a long preamble for PHY synchronization. The preamble is followed by a frame control header (FCH) burst and several DL bursts. A DL frame prefix (DLFP), which is contained in the FCH, specifies the burst profile and length for the first DL burst (at most four) via the information element (IE). It is noted that each DL burst may contain an optional preamble and more than one MAC PDUs that are destined for the same or different SSs. The first MAC PDU followed by the FCH is the DL-MAP message, which employs DL-MAP IEs to describe the remaining DL bursts. It is noted that the DL-MAP message can be excluded in the case that the DL subframe consists of less than five bursts. Nevertheless, the DL-MAP message must still be sent out periodically to maintain synchronization. A UL-MAP message immediately following the DL-MAP message denotes the usage of UL bursts via UL-MAP IEs. An interval usage code, corresponding to a burst profile, describes a set of transmission parameters, e.g., the modulation and coding type, and the forward error correction type. The DL interval usage code (DIUC) and UL interval usage code (UIUC) are specified in the DL channel descriptor (DCD) and UL channel descriptor (UCD) messages respectively. The BS broadcasts both the DCD and UCD messages periodically to define the characteristics of DL and UL physical channels respectively.

On the other hand, as can be seen from Fig. 1, the UL subframe starts with the contention intervals specified for both initial ranging and bandwidth request. It is noted that more than one UL PHY PDU can be transmitted after the contention intervals. Each UL PHY PDU consists of a short preamble and a UL burst, where the UL burst transports MAC PDUs for each specific SS. Moreover, a transmit/receive transition gap (TTG) and a receive/transmit transition gap (RTG) are inserted in between the DL and UL subframes and at the end of each frame respectively. These two gaps provide the required time for the BS to switch from the transmit to receive mode and vice versa.

2.2 Packet transmission mechanism

A connection in IEEE 802.16 PMP networks is defined as an unidirectional mapping between the BS and a SS, which is identified by a 16-bit connection identifier (CID). Two kinds of connections are defined in the IEEE 802.16 standard, i.e., management connections and transport connections. The management connections are utilized for delivering MAC management messages; while the transport connections are employed to transmit user data. During the initial ranging of a SS, a pair of UL/DL basic connections are established, which belong to a type of the management connections. It is noted that a single Basic CID is assigned to a pair of UL/DL basic connections, which is served as the identification number for the corresponding SS. Thus the SS uses the individual transport CID to request bandwidth for each transport connection while the BS arranges the accumulated transmission opportunity by addressing the Basic CID of the SS.

Figure 2 depicts the conventional packet transmission mechanism of IEEE 802.16 PMP networks. An exemplified network topology consisting of one BS and two neighboring SSs is shown in Fig. 2a. Two types of traffic exist in the network: inter-cell traffic and intra-cell traffic. For the inter-cell traffic, the source and the destination for each traffic flow are located in different cells, e.g., the traffic flow of SS_2 for accessing the Internet. On the other hand, the intra-cell traffic is defined while the source and the destination are situated within the same cell network, such as the traffic flow between SS_1 and SS_2 in Fig. 2a. Considering the scenario that SS_1 intends to communicate with its neighboring station SS_2, two transport connections are required to be established via the service flow management mechanism [1] for the intra-cell traffic, i.e., the UL transport connection from SS_1 to the BS and the DL transport connection from the BS to SS_2. Figure 2b illustrates the conventional transmission scheme in time sequence. In the most ideal case, the jth intra-cell packet, transmitted from SS_1 to the BS in the nth frame, will be forwarded to SS_2 in the $(n+1)$th frame by the BS. The rerouting process apparently requires twice of communication bandwidth for achieving the intra-cell packet transmission, which consequently increases control overhead by duplicating the corresponding data packets. Moreover, the delay time for packet-rerouting can be more than one half of a frame duration while the packet transmission from the BS to SS_2 is postponed to a latter DL subframe.

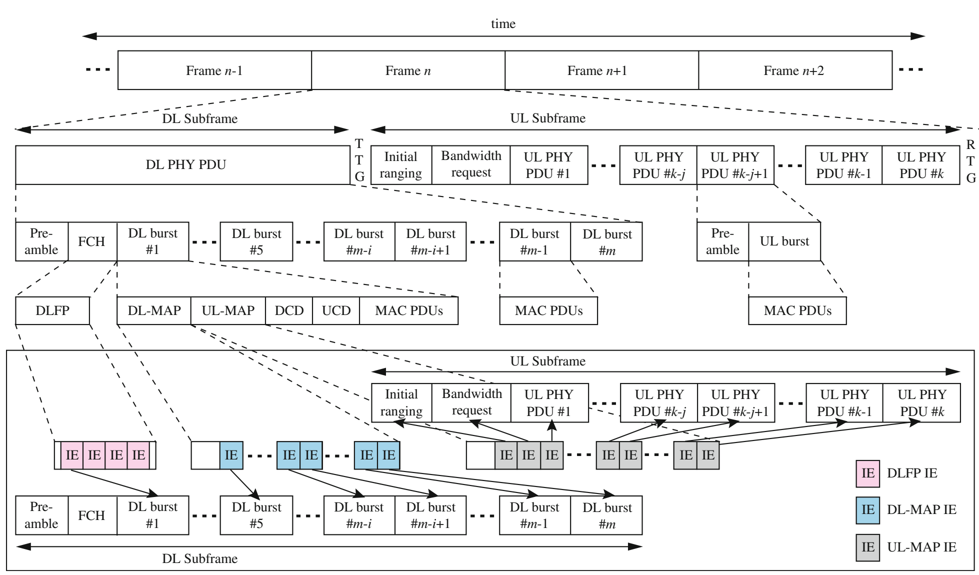

Fig. 1 Schematic diagram of IEEE 802.16 PMP OFDM frame structure with TDD

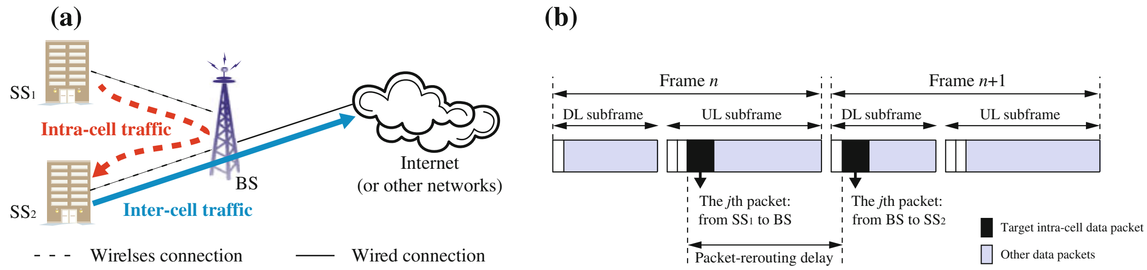

Fig. 2 Example of packet transmission in IEEE 802.16 PMP networks: **a** network topology and **b** conventional transmission scheme in time sequence

3 Proposed adaptive point-to-point communication (APC) approach

In this section, the proposed APC approach is presented for IEEE 802.16 PMP networks. The concept of the proposed scheme is to design a point-to-point directly communicable mechanism for SSs. Based on channel conditions among the BS and SSs, the packet transmission operation is switched automatically between the conventional indirect-link scheme and the proposed direct-link mechanism. Therefore, the following three conditions are designed to be satisfied in the proposed APC approach:

- *Flexible Condition*. This condition states that the APC approach is dynamically implemented. In other words, the direct communication between two SSs can be initiated, reactivated, and terminated by either the BS or the SS at any frame.
- *Contention-free Condition*. The inquiry for direct communication between two SSs may be requested by different pairs of SSs simultaneously. This condition indicates that the proposed APC approach should hold the contention-free processes, which include request, proceeding, and termination among those directly communicable pairs.
- *Backward-compatible Condition*. This condition indicates that the proposed APC approach is compatible and can be directly integrated with the existing protocols that are defined in the IEEE 802.16 standard.

It can be expected that the APC approach reduces both the required communication bandwidth and the control overhead for intra-cell traffic and also eliminates the packet-rerouting delay time. Furthermore, the network throughput is enhanced due to the automatic selection of efficient transmission manner between two schemes.

3.1 Architecture and management structures

Comparing with the original IEEE 802.16 PMP frame structure, the following two modifications are exploited by the proposed APC approach: (i) one or more point-to-point direct link (PDL) PHY PDUs are appended after the original DL PHY PDU in the DL subframe; and (ii) a specific number of UL PHY PDUs are replaced by the PDL PHY PDUs in the UL subframe. The schematic diagram of the IEEE 802.16 PMP frame structure with APC approach is illustrated in Fig. 3, where the adjustments are depicted by black rectangles. It can be observed that the proposed PDL subframe is designed to be a subset of a DL subframe and/or a UL subframe. The PDL subframe consists of one or more PDL PHY PDUs, which start with a short preamble followed by a PDL burst. Each PDL burst is designed to transport MAC PDUs for each specific SS. Moreover, the DL-PDL IE and UL-PDL IE are designed to be included in the DL-MAP and UL-MAP messages respectively, which are utilized to specify the burst profiles and lengths for the corresponding PDL bursts. In order to fully compatible with the existing IEEE 802.16 standard, three categories of management structures are proposed in the APC approach, including the DL-PDL IE and UL-PDL IE, the PDL subheader, and the PDL burst profile change request (PBPC-REQ) and response (PBPC-REP) messages. The functionalities and formats of the proposed structures are detailed as follows.

3.1.1 *DL-PDL IE and UL-PDL IE*

As shown in Fig. 3, the DL-MAP message defines the access to the DL channel; while the UL-MAP message characterizes and schedules the UL subframe. In other words, both the DL-MAP and UL-MAP messages adopt IEs along with DIUC and UIUC to describe the burst profiles and lengths of the corresponding DL and UL bursts respectively. The proposed DL-PDL IE and UL-PDL IE are designed to depict burst profiles and lengths of their corresponding PDLs in the DL and UL subframes respectively. The format of the DL-PDL IE is defined as in Table 1, which is considered as a new type of the extended DIUC dependent IE within the OFDM DL-MAP IE. The extended DIUC field identifies the IE type; while the size of IE is indicated in the length field. The duration field specifies the length of the corresponding PDL burst in the

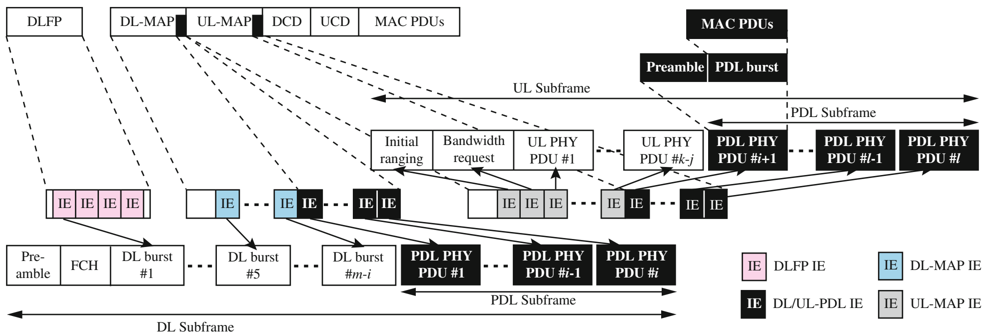

Fig. 3 Schematic diagram of IEEE 802.16 PMP OFDM frame structure with APC approach

Table 1 OFDM DL-PDL IE format

Syntax	Size (bit)
DL_PDL_IE() {	–
Extended DIUC	4
Length	4
DIUC	4
Duration	12
}	–

Table 2 OFDM UL-PDL IE format

Syntax	Size (bit)
UL_PDL_IE() {	–
Extended UIUC	4
Length	4
UIUC	4
Padding nibble, if needed	4
}	–

OFDM symbols. On the other hand, the proposed UL-PDL IE (as defined in Table 2) is designed to be a new type of the UL extended IE that is contained in the OFDM UL-MAP IE. It is noticed that both the proposed DL-PDL IE and UL-PDL IE are designed to conform to the formats of the DL-MAP dummy IE and UL-MAP dummy IE, respectively, which are defined in the IEEE 802.16 standard to support newly developed IEs.

3.1.2 PDL subheader

In the original IEEE 802.16 standard, six types of subheaders have been specified immediately followed by the generic MAC header. The proposed PDL subheader is designed to be a new type of per-PDU subheader that can be transmitted in both the DL and UL directions. It is utilized to implement the request, response, announcement, and termination of the APC approach. The presence of the

Table 3 PDL subheader format

Syntax	Size (bit)
PDL Subheader() {	–
Type	3
Location Type (LT)	2
if (Type == 000) {	–
SSID	48
LI_IE()	64
}	–
if (Type == 001)	–
CID	16
if (Type == 010) {	–
if (LT == 01)	–
LI_IE()	64
}	–
if (Type == 011) {	–
SINR	8
if (LT == 10)	–
LI_IE()	64
}	–
if (Type == 1xx) {	–
CID	16
CID	16
for (i = 1; i <= n; i++)	–
CID	16
}	–
Reserved	3
}	–

PDL subheader is indicated by a reserved bit in the generic MAC header. Table 3 illustrates the format of the PDL subheader; while its encoded type field is shown in Table 4. The location type (LT) field (as shown in Table 5) within the PDL subheader is adopted to either request or present the location information (LI) IE which includes the latitude, the longitude, and the altitude information [15]. The usages of the location information will further be explained in Subsect. 3.2.

Table 4 Type field encodings for the PDL subheader

Type	PDL subheader type
000	PDL request from source SS to BS
001	PDL request from BS to destination SS
010	PDL response from source SS to BS
011	PDL response from destination SS to BS
100	PDL termination request from SS
101	PDL announcement for termination
110	PDL announcement for confirming the request
111	PDL request from BS to considered SSs

Table 5 Location Type field encodings for requesting/presenting location information

LT	DL/UL
00	Not request/present
01	Request/present source SS's location information
10	Request/present destination SS's location information
11	Request both SSs' location information/–

3.1.3 PBPC-REQ and PBPC-REP messages

In the IEEE 802.16 standard, the adaptive modulation and coding (AMC) is exploited as the link adaption technique to improve the network performance on time-varying channels. The BS selects an adequate modulation and coding scheme (MCS) for the SS based on the reported signal-to-interference and noise ratio (SINR) value. The selected MCS is specified in the burst profile and is represented by the DIUC and UIUC values for the DL and UL directions respectively. Moreover, the BS permits the changes in the DIUC value that are suggested by the SS via the burst profile change request message. Similarly, both the proposed PBPC-REQ and PBPC-REP messages are designed to change the MCS for the PDL, where the format of both messages are shown in Table 6. The PBPC-REQ message is utilized to request the adjustment of the PDL interval usage code (PIUC) value for the PDL burst. The BS will respond with the proposed PBPC-REP message for either confirming or denying the alteration in the PIUC value. It is noticed that the PIUC value represents either the DIUC in DL direction or the UIUC in the UL direction. The operation of the PBPC-REQ and PBPC-REP messages will be shown in the following subsection.

3.2 Procedures of APC approach

The proposed APC approach is exploited after the establishment of the original transport connections among the BS and SSs. Considering a basic IEEE 802.16 PMP network that consists of a BS and two SSs, an intra-cell traffic

Table 6 PBPC-REQ/REP message format

Syntax	Size (bit)
PBPC-REQ/REP_Message_Format(){	–
Management Message Type	8
Reserved	4
CID	16
PIUC	4
Configuration Change Count	8
}	–

flow is existed between the SSs. Two transport connections are established for packet transmission, i.e., the UL transport connection (with CID $= K_1$) from the source station SS_s to the BS and the DL transport connection (with CID $= K_2$) from the BS to the destination station SS_d. It is noted that K_1 and K_2 are denoted as specific CID values. Four procedures are contained in the proposed approach including link request and information collection, admission control and link establishment, direct communication, and link termination. The detail of each procedure is described as follows.

3.2.1 Link request and information collection

The initialization of the APC approach is achieved by conducting the link request and information collection. The source–destination pair (SS_s, SS_d) that anticipates to establish the direct link are required to provide their location information and channel conditions to the BS. It is assumed that the SSs can acquire their location information by either using the GPS or performing network-based location estimation techniques [16, 17]. The collected information will be utilized in the admission control and link establishment procedure as will be explained in the next subsection. Figure 4 illustrates an exemplified message flows of the APC initialization.

In the case that SS_s intends to conduct direct communication with SS_d, as shown in Fig. 4a, it initiates the APC approach by attaching a PDL subheader to a data packet that will be delivered to the BS. The PDL subheader is utilized to request a direct link establishment with SS_d, where the Type field in the subheader is denoted as 000 and the 48-bit MAC address of SS_d is filled in the SSID field (as shown in Tables 3 and 4). The LT field is assigned as 01 and the location information of SS_s will be filled into the corresponding LI IE. As the BS receives the requesting PDL subheader from the SS_s, the BS will attach a PDL subheader (with Type field = 001) to a data packet and conduct the transmission to SS_d. The transport CID K_1 will be carried in the subheader for indicating that SS_s is the source of the direct communication, and it will send a

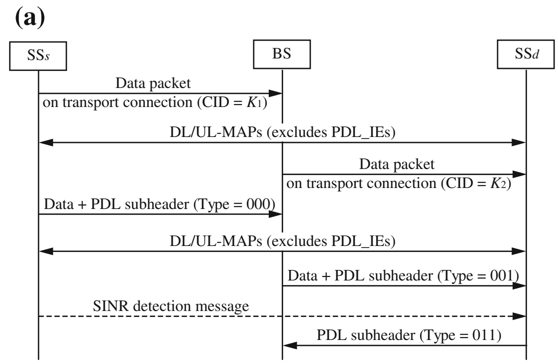

Fig. 4 Schematic diagram of link request and information collection procedure in APC approach: **a** SS-initiated APC approach and **b** BS-initiated APC approach

SINR detection message via that connection. If the BS does not possess the location information of SS_d, it will set the LT field as 10 for requesting the location information of SS_d.

Furthermore, the BS will arrange a DL burst for SS_s with the assignment in the corresponding DL-MAP message. The CID of the UL transport connection (i.e., CID $= K_1$) will be recorded in the CID field of the DL-MAP IE; while the DIUC field is set with the value that corresponds to the BPSK 1/2 MCS. Specifically, the DL burst for the connection with CID K_1 is prepared for SS_s to transmit an SINR detection message to SS_d by using the BPSK 1/2 MCS. It is noticed that the UL transport CID will be assigned in the DL subframe, which will not happen by adopting the conventional mechanism. Therefore, the SS_s is aware that the DL burst for the UL transport CID is utilized to transmit the SINR detection message. After receiving the PDL subheader and the SINR detection message from the BS and SS_s respectively, SS_d will transmit a response PDL subheader with Type 011. The average SINR value calculated from the SINR detection message will also be recorded in the response PDL subheader.

The BS-initiated APC approach is shown in Fig. 4b. Contrary to the SS-initiated APC approach, the BS actively announces the PDL request along with a PDL subheader (with Type field = 111) to the specific SSs, i.e., SS_s and SS_d. The Basic CIDs for both SS_s and SS_d are specified within the first two CID fields of the PDL subheader as shown in Table 3; while the corresponding UL transport CID K_1 is written in the third CID field. As SS_s receives the requesting PDL subheader with LT = 01 or 11 from the BS, the SS_s will attach a PDL subheader (with Type field = 010) to a data packet that will be delivered to the BS. Correspondingly, the SS_s will utilize the replying PDL subheader to provide its location information that is requested by the BS. The remaining procedures of the BS-initiated APC approach are similar to that of the SS-initiated case, such as the SINR detection procedure between SS_s and SS_d, and the response PDL subheader from SS_d.

It is noted that the timer-based retransmission technique, utilized in the current IEEE 802.16 system, is exploited in the proposed procedures to handle the missing messages. For example, in the procedure of link request and information collection, the BS sends the request message to SS_d and waits for the corresponding response message. If the BS did not obtain any response from SS_d within a predefined time interval, the BS will retransmit the request message to SS_d and reset the timer for acquiring the response.

3.2.2 *Admission control and link establishment*

After receiving the response PDL subheader that is transmitted from SS_d, the BS will execute the admission control and link establishment procedure in order to either confirm or deny the direct communication request between SS_s and SS_d. Two admission constraints for direct communication are considered in the proposed APC approach as follows, including the throughput-oriented and the energy-oriented constraints.

- *Throughput-Oriented (TO) Constraint*. In order to enhance the efficiency for data transmission, channel conditions among the BS and the (SS_s, SS_d) pair should be taken into account. The transmission throughput resulted from the direct communication should be designed to be higher than that from the conventional IEEE 802.16 mechanism. Seven MCSs supported in the IEEE 802.16 standard associated with various number of data bits are adopted for data transmission under different channel conditions. Consequently, the TO constraint ($\mathcal{C}_1$) for the direct communication can be represented as

$$\mathcal{C}_1: \quad \frac{1}{R(SS_s, SS_d)} < \frac{1}{R(SS_s, BS)} + \frac{1}{R(BS, SS_d)},$$

where $R(x, y)$ represents the data rate between x and y. In other words, the constraint $\mathcal{C}_1$ indicates that the required time for transmitting one bit by SS_s via the direct transmission should be less than that by adopting the BS as the forwarding medium.

- *Energy-Oriented (EO) Constraint*. In wireless communication system, data transmission range for each station is proportional to its corresponding transmission power. In order to avoid additional power consumption introduced by exploiting the APC approach, the EO constraint for the direct communication is designed as

$$\mathcal{C}_2: \quad D(SS_s, SS_d) \leq D(SS_s, BS),$$

where $D(x, y)$ denotes the relative distance between x and y. The EO constraint $\mathcal{C}_2$ represents that the transmission power utilized by SS_s for achieving direct transmission is adjusted to be equal to or less than that as specified in the conventional IEEE 802.16 mechanism.

The BS will determine its admission for the direct communication request by using the collected information and the constraints $\mathcal{C}_1$ and $\mathcal{C}_2$. It is noted that the constraints $\mathcal{C}_1$ and $\mathcal{C}_2$ can be exploited either jointly or separately. The performance of the separately implemented mechanisms, i.e., the APC-TO and the APC-EO approaches, will be evaluated via the simulation results in Sect. 5.2. The confirming results will be broadcasted along with a PDL subheader (with Type field = 110) by the BS. The Basic CIDs for both SS_s and SS_d are written within the the first two CID fields of the PDL subheader as shown in Table 3; while the corresponding confirmed connections are recorded in the remaining CID fields. In the case that all the connections belonging to the indirect transmission from SS_s to SS_d are confirmed by the BS, the individual CIDs will be replaced by the Basic CID of SS_s. In other words, the Basic CID of SS_s will be filled into the third CID field in order to reduce the excessive control overhead that is caused by the individually confirmed CIDs. Consequently, the BS will arrange the corresponding PDL bursts for conducting direct link communication in the subsequent frames.

3.2.3 Direct communication

After receiving the confirmation announcement, the considered SSs will activate the procedure of direct communication. According to the received MAPs associated with the PDL IEs, SS_s will conduct packet transmission directly to SS_d within the PDL bursts. Moreover, SS_d will continuously observe and evaluate the cannel condition for the direct link with the adaptation to an appropriate MCS. SS_d will calculate the SINR of the received data packet and compare it with the receiver SNR range of the current MCS. If the existing MCS is observed to be improper for the current channel condition, SS_d will initiate a PBPC-REQ message to the BS for suggesting an appropriate MCS via the PIUC value. Consequently, the BS will respond with a PBPC-REP message with a recommended PIUC value. If the PIUC values from both the PDPB-REQ and the PBPC-REP messages are perceived to be the same, the request for the change of MCS will be accepted. If the condition is not satisfied, the PIUC value will remain unaltered.

It is worthwhile to mention that the bandwidth requests are conducted by an SS based on individual transport connection. On the other hand, the bandwidth grant from the BS is executed according to the accumulated requests from the SS. In other words, the bandwidth grant is addressed to the Basic CID of the corresponding SS, not to the individual transport CIDs. As a result, the CID specified for the PDL burst becomes the Basic CID of SS_s. Furthermore, in order to fully backward-compatible with the existing specification, procedures for bandwidth request and allocation as specified in the IEEE 802.16 standard are implemented within the proposed APC approach. Figure 5 illustrates the bandwidth request procedure of the APC approach. It can be observed that the BS preserves PDL bursts for non-polling based service periodically. Moreover, the BS will continue to provide unicast bandwidth request opportunity for the polling-based services based on the original transport CIDs of SS_s. The unicast bandwidth grant of those services will consequently be assigned to the PDL burst based on the Basic CID of SS_s.

3.2.4 Link termination

The procedure for link termination occurs as one of the following two conditions is satisfied: (i) the channel condition of the direct link is becoming worse than that from

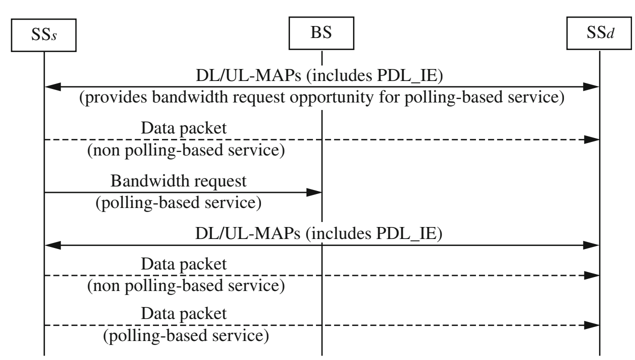

Fig. 5 Schematic diagram of bandwidth request procedure in APC approach

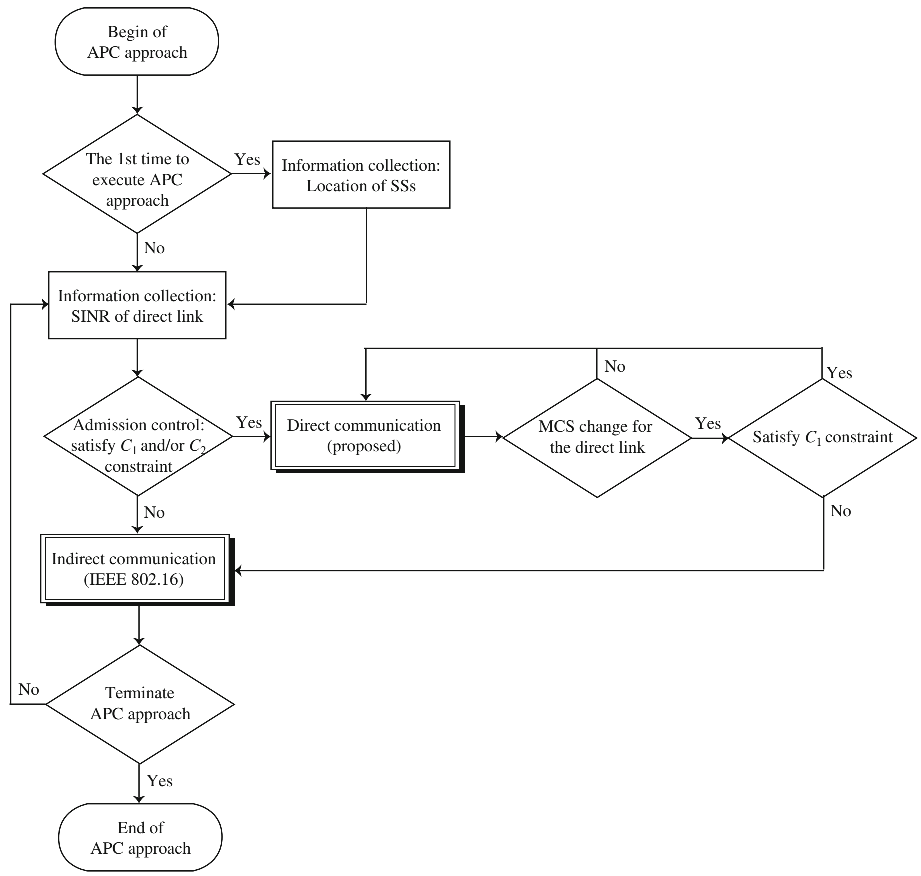

Fig. 6 Flow diagram of transmission switching between direct and indirect communications in APC approach

the indirect channels (i.e., via the BS); (ii) the direct communication is determined to be ceased. It is noted that the link termination can be initiate by either the BS or the SSs. In the SS-initiated termination procedure, the SS will transmit a termination PDL subheader to the BS (with Type field = 100). As the message is received by the BS, it will broadcast an announcement along with a PDL subheader (with Type field = 101) to both SS_s and SS_d regarding the termination of the direct communication link. As a result, the BS and the associated SSs will return to adopt the original packet transmission mechanism as defined in the IEEE 802.16 standard.

Figure 6 depicts the flowchart of switching process for packet transmission in the proposed APC approach. The entire process is constructed by the aforementioned procedures. It can be observed that switching between direct and indirection communications is dominated by the constraint $\mathcal{C}_1$. In other words, the APC approach always selects the most efficient transmission for intra-cell traffic based on channel conditions among the BS and the SSs. It is noted that the channel conditions can be obtained via calculating the SINR value periodically. Consequently, it can be expected that the network throughput is enhanced while the proposed APC approach is exploited.

4 Numerical analysis

In this section, an analytical study of the IEEE 802.16 PMP OFDM frame structure with TDD is conducted. This study aims at analyzing the saturation user throughput as well as the corresponding overhead that can be achieved in the IEEE 802.16 PMP networks. The user throughput is defined as the data bits per second which are received by the destination station in the considered network. Both the conventional packet transmission mechanism and the proposed APC approach are analyzed while taking into account the MAC and PHY overheads. Since the saturation user throughput of the IEEE 802.16 network is the primary concern in this study, only one BS and two SSs are considered as shown in Fig. 2a. It is assumed that both inter-cell traffic and intra-cell traffic flows exist in the considered network. Each inter-cell traffic flow is attached to either a UL or a DL connection; while the intra-cell traffic flow is resulted from the combination of both a UL and a DL connections. Therefore the number of inter-cell connections for a specific SS_k can be represented as

$$n_k = n_k^d + n_k^u, \tag{1}$$

where n_k^d and n_k^u are the numbers of inter-cell connections for SS_k in the DL and UL directions respectively. On the other hand, the number of intra-cell connections for SS_k can be represented as

$$m_k = m_k^d + m_k^u + \overline{m}_k^d + \overline{m}_k^u, \quad (2)$$

where m_k^d and m_k^u denote the numbers of one-hop intra-cell connections in the DL and UL directions for SS_k respectively. The term one-hop indicates that BS is assigned as either the source or the destination station for the intra-cell connection. On the other hand, the numbers of two-hop intra-cell connections in the DL and UL directions for SS_k are represented as $\overline{m}_k^d$ and $\overline{m}_k^u$. In other words, both the source and destination stations are designated to SSs; while SS_k belongs to one of these two SSs.

4.1 Conventional mechanism

In this subsection, both the saturation user throughput and the corresponding overhead for the conventional mechanism of the IEEE 802.16 network will be derived. Considering that S_f represents one frame duration in the unit of OFDM symbols, the total number of available OFDM symbols S_{av} within a frame can be obtained as

$$S_{av} = S_f - S_{ttg} - S_{rtg}, \quad (3)$$

where S_{ttg} and S_{rtg} denote the durations of TTG and RTG in OFDM symbols respectively. Without loss of generality, it is assumed that a frame duration is evenly partitioned by the DL and UL subframes for analytical convenience. Different durations of DL and UL subframes can also be analyzed in similar manner. However, the ratio of DL subframe to UL subframe should be a constant value for all the BSs in an IEEE 802.16 network. If the ratio is different for each BS, significant inter-cell interference will appear in the entire network. Therefore, the durations of both the DL subframe $\left(S_f^d\right)$ and the UL subframe $\left(S_f^u\right)$ in OFDM symbols can be represented as

$$S_f^d = \left\lfloor \frac{S_{av}}{2} \right\rfloor, \quad (4)$$

$$S_f^u = S_{av} - S_f^d. \quad (5)$$

In order to obtain the user throughput, both the MAC and PHY overheads should be removed from the available raw bandwidth. According to the assumptions as mentioned above, the MAC and PHY overheads for a DL subframe in the conventional mechanism can be computed as

$$S_{oh}^d = S_{lp} + S_{fch} + \left\lceil \frac{2B_{gmh} + 2B_{crc} + B_{map}^d + B_{ie}^d + B_{map}^u + 5B_{ie}^u}{C_{map}} \right\rceil, \quad (6)$$

where S_{lp} and S_{fch} are the durations of long preamble and FCH in OFDM symbols, which are regarded as the PHY overhead. The notations B_{gmh} and B_{crc} represent the size of generic MAC header and CRC in bytes; while B_{map}^d, B_{map}^u, B_{ie}^d, and B_{ie}^u are the size of DL-MAP, UL-MAP, DL-MAP IE, and UL-MAP IE in bytes respectively. It is noted that all these parameters are designated as the MAC overhead. Moreover, the bytes per OFDM symbol for transmitting these MAP messages is denoted as C_{map}, whose value depends on the selection of the MCS. Since only two SSs are considered in the analytical model, three DL bursts are described in the FCH, i.e., for broadcasting MAP messages and transmitting data packets to SS_1 and SS_2 individually. The DL-MAP message contains only an end of map IE; while the UL-MAP message associated with UL-MAP IEs describe five bursts, including initial ranging, bandwidth request, two data grants for SS_1 an SS_2 individually, and end of map IE. Furthermore, both the DL-MAP and UL-MAP messages are individually attached with a generic MAC header and a CRC as denoted in (6). On the other hand, the MAC and PHY overhead for a UL subframe consists of two contention intervals (i.e., the initial ranging and the bandwidth request) and the short preambles. Since there are two SSs in considered, two short preambles will be transmitted in total by both SS_1 and SS_2. Therefore, the overhead for a UL subframe can be obtained as

$$S_{oh}^u = S_{ci} + 2S_{sp}, \quad (7)$$

where S_{ci} and S_{sp} are the durations of contention intervals and a single short preamble in OFDM symbols respectively.

Recall that the main objective of this study is to determine the saturation user throughput and the corresponding overhead of IEEE 802.16 PMP networks. The focus is to compute the maximum number of MAC PDUs that can be transmitted and received by a station within a frame respectively. It is assumed that there is always a packet to be transmitted in each the connection for any of the SS. Moreover, based on connection-oriented feature of the IEEE 802.16 MAC protocol, the resource scheduling within the BS is implemented on a per connection basis. Therefore, each connection is designed to receive a fair share of service. In other words, the available bandwidth for an SS in a frame depends on the number of connections it possesses. Based on (1), (2), (4) and (6), the maximum number of MAC PDUs that can be transmitted by the BS to SS_k during a DL subframe is computed as

$$\varphi_k^d(B_{pkt}, C_k) = \left\lfloor \frac{\left(S_f^d - S_{oh}^d\right) \cdot \frac{n_k^d + m_k^d + \overline{m}_k^d}{\sum_{i=1}^{2}\left(n_i^d + m_i^d + \overline{m}_i^d\right)} \cdot C_k}{B_{gmh} + B_{pkt} + B_{crc}} \right\rfloor, \quad (8)$$

where B_{pkt} represents the mean size of MAC service data unit (SDU) in bytes; while C_k is the bytes per OFDM symbol for SS_k to transmit packets. Similarly, the maximum number of MAC PDUs that is transmitted by SS_k to the BS during a UL subframe can be obtained as

$$\varphi_k^u(B_{pkt}, C_k) = \left\lfloor \frac{\left(S_f^u - S_{oh}^u\right) \cdot \frac{n_k^u + m_k^u + \overline{m}_k^u}{\sum_{i=1}^{2}\left(n_i^u + m_i^u + \overline{m}_i^u\right)} \cdot C_k}{B_{gmh} + B_{pkt} + B_{crc}} \right\rfloor. \quad (9)$$

According to the definition of the user throughput, only the packets that are received by the destination stations should be considered. The maximum number of effective MAC PDUs for SS_k in a DL subframe will still be the same as (8), i.e.,

$$\varepsilon_k^d(B_{pkt}, C_k) = \varphi_k^d(B_{pkt}, C_k). \quad (10)$$

However, the maximum number of effective MAC PDUs for SS_k in a UL subframe becomes

$$\varepsilon_k^u(B_{pkt}, C_k) = \left\lfloor \frac{\left(S_f^u - S_{oh}^u\right) \cdot \frac{n_k^u + m_k^u}{\sum_{i=1}^{2}\left(n_i^u + m_i^u + \overline{m}_i^u\right)} \cdot C_k}{B_{gmh} + B_{pkt} + B_{crc}} \right\rfloor. \quad (11)$$

It is noted that the parameter $\overline{m}_k^u$ as appeared in (9) is not counted since it denotes the number of two-hop intra-cell connections in the UL direction, which should not be considered in the computation of effective throughput in (11). Based on (10) and (11), the user throughput of SS_k in the DL and UL subframes, respectively, can be derived as

$$T_k^d(B_{pkt}, C_k) = \frac{\varepsilon_k^d(B_{pkt}, C_k) \cdot 8B_{pkt}}{L_f}, \quad (12)$$

$$T_k^u(B_{pkt}, C_k) = \frac{\varepsilon_k^u(B_{pkt}, C_k) \cdot 8B_{pkt}}{L_f}, \quad (13)$$

where L_f denotes the duration of a frame in seconds. Combining (12) and (13), the saturation user throughput that is achieved in the IEEE 802.16 PMP network can therefore be computed as the sum of the user throughput of each SS, i.e.,

$$T_{conv}^{max}(B_{pkt}, C_k) = \sum_{k=1}^{2}\left[T_k^d(B_{pkt}, C_k) + T_k^u(B_{pkt}, C_k)\right]. \quad (14)$$

Furthermore, the corresponding overhead in terms of time per frame can be derived from (6) and (7) as

$$\begin{aligned} O_{conv}^{max}(B_{pkt}, C_k) &= \left(S_{ttg} + S_{rtg} + S_{oh}^d + S_{oh}^u\right) \cdot L_s \\ &+ \sum_{k=1}^{2} \frac{\left[\varphi_k^u(B_{pkt}, C_k) - \varepsilon_k^u(B_{pkt}, C_k)\right] \cdot (B_{gmh} + B_{pkt} + B_{crc})}{C_k} \cdot L_s \\ &+ \sum_{k=1}^{2} \frac{\left[\varepsilon_k^d(B_{pkt}, C_k) + \varepsilon_k^u(B_{pkt}, C_k)\right] \cdot (B_{gmh} + B_{crc})}{C_k} \cdot L_s, \end{aligned} \quad (15)$$

where L_s is the duration of an OFDM symbol in seconds. It is noted that the second term in (15) represents the overhead caused by the duplication of the data packets; while the MAC overhead of the received data packets is specified in the last term.

4.2 Proposed APC approach

In the proposed APC approach, the BS will arrange specific time interval for the SSs to conduct direct communication. Since the saturation user throughput of IEEE 802.16 PMP network is the main concern of this study, it is assumed that all the direct connections are scheduled at the end of the UL subframe regardless of any specific scheduling algorithm. Therefore, the MAC and PHY overhead for a DL subframe by adopting the APC approach can be computed as

$$\begin{aligned} \mathbb{S}_{oh}^d &= S_{lp} + S_{fch} \\ &+ \left\lceil \frac{2B_{gmh} + 2B_{crc} + B_{map}^d + B_{ie}^d + B_{map}^u + 7B_{ie}^u + 2B_{ie}^{updl}}{C_{map}} \right\rceil, \end{aligned} \quad (16)$$

where B_{ie}^{updl} represents the size of UL-PDL IE in bytes. It is noted that since the UL-PDL IE is an extended IE within the UL-MAP IE, additional two UL-MAP IEs and two UL-PDL IEs are required to arrange the direct transmission between the SSs. Furthermore, the overhead for a UL subframe with the APC approach becomes

$$\mathbb{S}_{oh}^u = S_{ci} + 4S_{sp}. \quad (17)$$

It is noted that an additional short preamble is required for the PHY synchronization of SS_1 and SS_2 respectively. Recall that each connection receives a fair share of service is assumed in this study. With (3), (16), and (17), the duration of PDL subframe in OFDM symbols can be obtained as

$$\mathbb{S}_{pdl} = \left(S_{av} - \mathbb{S}_{oh}^d - \mathbb{S}_{oh}^u\right) \cdot \frac{\sum_{i=1}^{2} \overline{m}_i^u}{\sum_{i=1}^{2}\left(n_i + m_i - \overline{m}_i^d\right)}. \quad (18)$$

Since only two SSs are considered in this study, the number of two-hop intra-cell connections in the UL direction for SS_1 equals to that in the DL direction for SS_2 and vice versa, i.e., $\overline{m}_1^u = \overline{m}_2^d$ and $\overline{m}_2^u = \overline{m}_1^d$. Therefore, the numbers of direct connections and total connections in the considered network are $\sum_{i=1}^{2} \overline{m}_i^u$ and $\sum_{i=1}^{2}\left(n_i + m_i - \overline{m}_i^d\right)$ respectively. The number of remaining OFDM symbols in a frame by exploiting the APC approach becomes

$$\mathbb{S}_{av} = S_f - S_{ttg} - S_{rtg} - \mathbb{S}_{pdl}. \quad (19)$$

Similar to (5), the duration of DL subframe $\left(\mathbb{S}_f^d\right)$ and UL subframe $\left(\mathbb{S}_f^u\right)$ in OFDM symbols by adopting the APC approach can be represented as

$$\mathbb{S}_f^d = \left\lfloor \frac{\mathbb{S}_{av}}{2} \right\rfloor, \tag{20}$$

$$\mathbb{S}_f^u = \mathbb{S}_{av} - \mathbb{S}_f^u. \tag{21}$$

Consequently, the maximum number of MAC PDUs that can be transmitted by the BS to SS_k during a DL subframe can be computed as

$$\vartheta_k^d(B_{pkt}, C_k) = \left\lfloor \frac{\left(\mathbb{S}_f^d - \mathbb{S}_{oh}^d\right) \cdot \frac{n_k^d + m_k^d}{\sum_{i=1}^{2}\left(n_i^d + m_i^d\right)} \cdot C_k}{B_{gmh} + B_{pkt} + B_{crc}} \right\rfloor. \tag{22}$$

It is noted that the number of two-hop intra-cell connections in the DL direction $\overline{m}_k^d$ as appeared in (8) is not considered in (22) due to the adoption of the proposed APC approach. On the other hand, the maximum number of MAC PDUs that are delivered by SS_k during a UL subframe is acquired as

$$\vartheta_k^u(B_{pkt}, C_k) = \left\lfloor \frac{\left(\mathbb{S}_f^u - \mathbb{S}_{oh}^u\right) \cdot \frac{n_k^u + m_k^u}{\sum_{i=1}^{2}\left(n_i^u + m_i^u\right)} \cdot C_k}{B_{gmh} + B_{pkt} + B_{crc}} \right\rfloor + \left\lfloor \frac{\mathbb{S}_{pdl} \cdot \frac{\overline{m}_k^u}{\overline{m}_1^u + \overline{m}_2^u} \cdot C_{pdl}}{B_{gmh} + B_{pkt} + B_{crc}} \right\rfloor, \tag{23}$$

where C_{pdl} represents the bytes per OFDM symbol for direct transmission. It is noted that the second term in (23) specifies the maximum number of MAC PDUs that are transmitted by SS_k within the direct connections. Furthermore, the maximum number of effective MAC PDUs for SS_k in a DL subframe is equal to (22); while that in a UL subframe will be the same as (23). Based on (22) and (23), the user throughput of SS_k in the DL and UL subframes, respectively, can be obtained as

$$\mathbb{T}_k^d(B_{pkt}, C_k) = \frac{\vartheta_k^d(B_{pkt}, C_k) \cdot 8B_{pkt}}{L_f}, \tag{24}$$

$$\mathbb{T}_k^u(B_{pkt}, C_k) = \frac{\vartheta_k^u(B_{pkt}, C_k) \cdot 8B_{pkt}}{L_f}. \tag{25}$$

As a result, the saturation user throughput by adopting the APC approach can be acquired as

$$\mathbb{T}_{apc}^{max}(B_{pkt}, C_k) = \sum_{k=1}^{2}\left[\mathbb{T}_k^d(B_{pkt}, C_k) + \mathbb{T}_k^u(B_{pkt}, C_k)\right]. \tag{26}$$

Similarly, the corresponding overheads in terms of time per frame is obtained as

$$\mathbb{O}_{apc}^{max}(B_{pkt}, C_k) = \left(S_{ttg} + S_{rtg} + \mathbb{S}_{oh}^d + \mathbb{S}_{oh}^u\right) \cdot L_s + \sum_{k=1}^{2} \frac{\left[\vartheta_k^d(B_{pkt}, C_k) + \vartheta_k^u(B_{pkt}, C_k)\right] \cdot (B_{gmh} + B_{crc})}{C_k} \cdot L_s. \tag{27}$$

5 Performance evaluation

In this section, the analytical results obtained from the previous section will be validated. Furthermore, extensive simulations are performed in order to evaluate the performance of the proposed APC approach in comparison with the conventional packet transmission mechanism in IEEE 802.16 PMP networks. It is noted that simulations are carried out by an event-driven IEEE 802.16 MAC simulator written in MATLAB. All the required procedures and functions for DL/UL data transmission and UL bandwidth request/grant have been implemented in the simulator.

5.1 Validation of analytical results

Simulations are performed in order to validate the analytical models as derived in the previous section. One BS along with two SSs as shown in Fig. 2a are considered in the network, where 20 traffic flows are assumed. Since the saturation user throughput is the main concern in the derivation of the analytical models, the packet buffer for each connection is designed to be nonempty during the entire simulation time. Furthermore, same MCS is utilized within both the DL and UL transmission for each SS. Figures 7, 8, and 9 illustrate the performance evaluation obtained from both the analytical models (i.e., denoted as "Ana") and the simulation results (i.e., indicated as "Sim") under various scenarios, i.e., with different MCS, MAC SDU size, and percentage of intra-cell traffic flow. The performance comparisons between the proposed APC approach and the conventional IEEE 802.16 packet transmission scheme are also shown in these figures.

Figure 7 illustrates the performance validation for both the saturation user throughput and the corresponding overhead under various MCSs as listed in Table 7. It is noted that each MCS is assigned with an index, where the higher value of index represents the usage of a more efficient MCS, e.g., MCS = 0 corresponds to BPSK 1/2 and MCS = 6 indicates 64-QAM 3/4. As can be seen in Fig. 7a, higher saturation user throughput can be reached with the more efficient MCS in the both schemes. Since the proposed APC approach conducts direct transmission between two SSs, the saturation user throughput from the APC approach is almost twice than that of the conventional scheme under the same MCS. It can also be found that the results obtained from the analytical models almost coincide with that from the simulations under all the scenarios. However, slightly lowered performance is observed from the analytical results. This can be attributed to the reason that both the fragmentation and packing of packets are ignored in the numerical analysis. There is more tendency

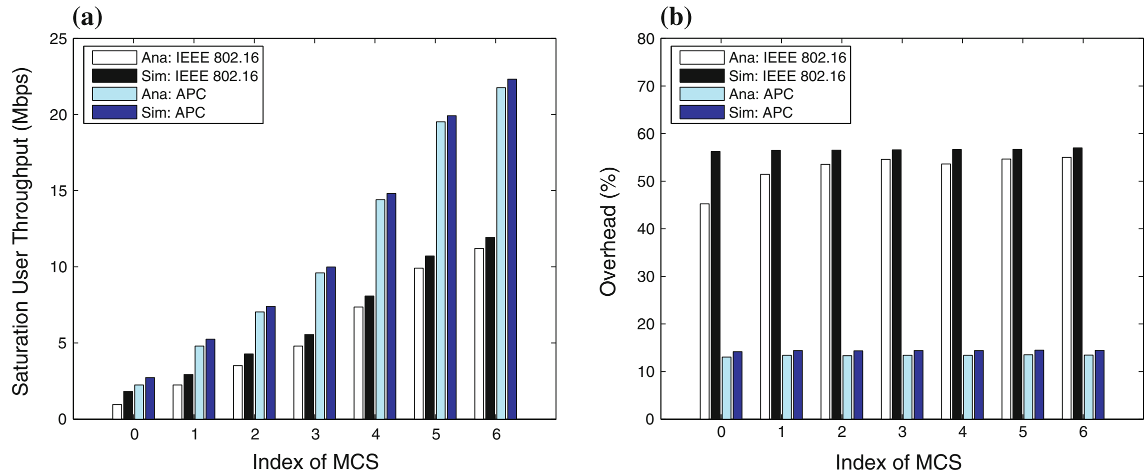

Fig. 7 Performance comparison: **a** saturation user throughput versus index of MCS, and **b** overhead versus index of MCS

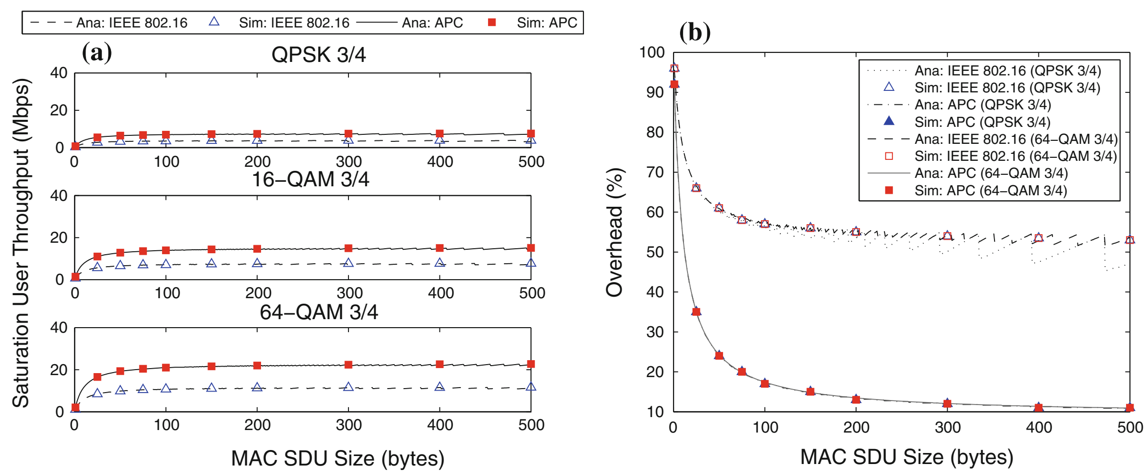

Fig. 8 Performance comparison: **a** saturation user throughput versus MAC SDU size, and **b** overhead versus MAC SDU size

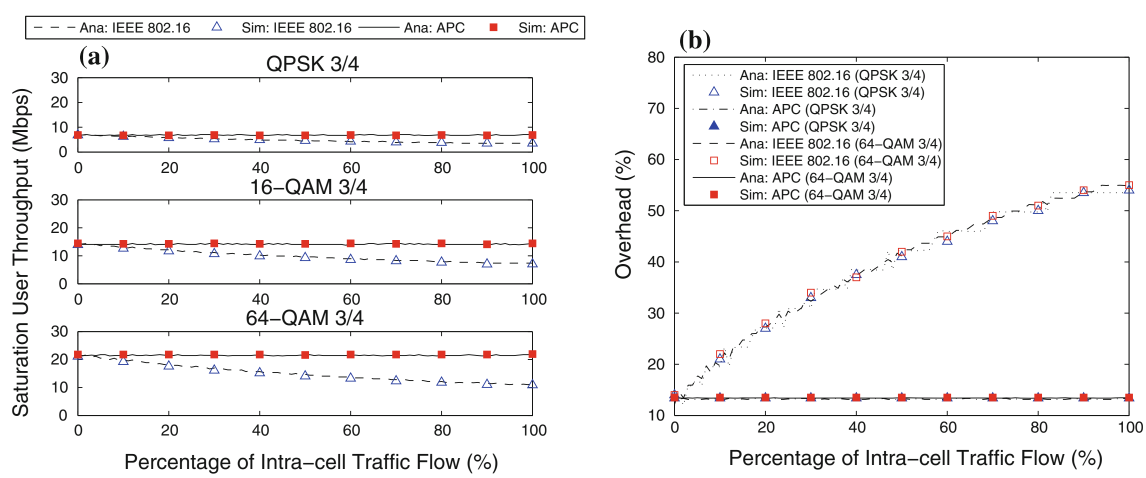

Fig. 9 Performance comparison: **a** saturation user throughput versus percentage of intra-cell traffic flow, and **b** overhead versus percentage of intra-cell traffic flow

Table 7 OFDM Modulation and Coding Schemes

MCS index	Modulation lever	Coding rate	Coded clock size (byte)	Raw data rate (Mbps)	Receiver SNR (dB)	Maximum *R* (m)
0	BPSK	1/2	24	2.8235	3.0	1,666.4
1	QPSK	1/2	48	5.6471	6.0	1,386.7
2	QPSK	3/4	48	8.4706	8.5	1,189.8
3	16-QAM	1/2	96	11.2941	11.5	990.15
4	16-QAM	3/4	96	16.9412	15.0	799.13
5	64-QAM	2/3	144	22.5882	19.0	625.51
6	64-QAM	3/4	144	25.4118	21.0	553.4

that the length of the OFDM symbols will not be longer enough to transmit an entire packet under insufficient MCS level, which result in decreased number of the transmitted packets.

The comparison of communication overhead under various MCSs is shown in Fig. 7b. For each scheme, it can be observed that the overhead is almost constant under various MCSs except for the analytical results with MCS $= 0$ and 1. Owing to the same reason that fragmentation and packing are neglected in the analytical models, more OFDM symbols becomes insufficient for transmitting a packet under lower level of MCS. Consequently, comparably less number of overhead is observed since these unused symbols are not counted as overhead in the analytical models. On the other hand, it can be seen that the APC approach results in comparably lower overhead in comparison with the conventional mechanism under different MCS levels. The performance difference between these two schemes can be explained via Eqs. (15) and (27), wherein the main reason is attributed to the duplication of forwarding packets that are generated in the conventional scheme.

Performance validation under various MAC SDU sizes is shown in Fig. 8. It is noted that the MCSs with QPSK 3/4, 16-QAM 3/4, and 64-QAM 3/4 are considered. It can be observed that the results obtained from the analytical models are consistent with that from the simulations in both schemes. Moreover, the proposed APC approach outperforms the conventional mechanism in both the user throughput (as in Fig. 8a) and the communication overhead (as in Fig. 8b) under different MAC SDU sizes. As shown in Fig. 8a, it can be expected that the saturation user throughput increases as the size of MAC SDU is augmented. Furthermore, the maximum saturation user throughput is observed to reach at around 200 bytes of MAC SDU size for both schemes. Therefore, the mean packet size of the MAC SDU is assumed as 200 bytes in the remaining performance evaluation. Figure 8b illustrates the performance comparison of the corresponding overhead under various MAC SDUs. Since the sizes of both the header and CRC within a packet remain constant, it is apparent that high communication overhead will be incurred while a smaller size of MAC SDU is transmitted. With the increase of the MAC SDU size, the overheads obtained from both schemes are decreased. However, due to the required packet forwarding via the BS, the conventional mechanism results in higher overhead in comparison with that from the proposed APC approach.

Figure 9 illustrates the performance comparison under the influence of inter-cell traffic flows. As shown in Fig. 9a, it can be observed that the same highest saturation user throughput are reached in both schemes while all the flows belong to the inter-cell traffic. The reason is attributed to the definition of user throughput, wherein the BS is treated as either a source or a destination station for an inter-cell traffic. By adopting the conventional mechanism, it can be expected that the saturation user throughput decreases as the percentage of intra-cell traffic flows is augmented due to the packet re-routing via the BS. On the other hand, the packets are directly transmitted from the source to the destination by exploiting the proposed APC approach, which results in the same level of saturation user throughput. Figure 9b shows the corresponding overhead with different percentages of intra-cell traffic flows in the network. Owing to the duplication of forwarding packets via the BS, it can be expected that the overhead from the conventional scheme increases as the percentage of intra-cell traffic flow is augmented. Nevertheless, the overhead resulting from the proposed APC approach remains at the same level under all the scenarios.

5.2 Performance comparison

In order to evaluate the effectiveness of the proposed APC approach, a more realistic simulation setup is performed in this subsection. A 19 cell-based wrap around topology [18] is considered as the simulation layout. Each cell consists of a centered BS and 20 uniformly distributed SSs. The mandatory path loss model defined as $PL(dB) = 130.19 + 37.6\log_{10}(R/1000)$ for IEEE 802.16 system [18] is adopted to reflect the channel conditions, where R is the distance between transmitter and receiver in unit of meter. The maximum value of R, calculated without the consideration of interference caused by other transmissions, for each MCS is listed in the last column of Table 7. The error model is defined by considering the difference between the default receiver SNR values as listed in Table 7 and the received SINR value obtained based on the path loss model. If the received SINR value is larger than the predefined SNR value for the corresponding MCS, the transmission packets can be successfully received by a receiver. Otherwise, the transmission is considered failed and the transmitter will resend the packets. Furthermore, the selective repeat automatic repeat-request mechanism is employed to perform the packet retransmission process.

In the simulation, both the intra-cell and inter-cell traffic flows are considered; while the source and destination of each flow are randomly selected. The packet arrival process of each flow is assumed to follow a Poisson process with rate λ in unit of packet per frame. The size of each packet is selected to follow the exponential distribution with the mean value of 200 bytes. Since the scheduling algorithm is not specified in the IEEE 802.16 standard, the deficit round robin (DRR) [19] and weighted round robin (WRR) [20] algorithms are selected as the BS's DL and UL schedulers respectively. The DRR algorithm is also utilized by the SS to share the UL grants that are provided by the BS for its corresponding UL connections. Table 8 lists the parameters that are adopted within the simulation. Figures 10, 11, and 12 show the performance comparisons among the proposed APC approach with the TO constraint (denoted as APC-TO) and EO constraint (denoted as APC-EO) respectively, and the conventional scheme (denoted as IEEE 802.16). Furthermore, the comparisons of direct communications conducted in either the DL subframe or the UL subframe are also shown in these figures.

Figure 10 illustrates the performance of user throughput, overhead, and latency under various traffic loads λ for each compared schemes. In this comparison, 200 intra-cell traffic flows with the same λ are considered. It is intuitive

Table 8 Simulation Parameters

Parameter	Value
OFDM symbol duration	34 μs
MAPs modulation	BPSK
Data modulation	QPSK, 16-QAM, 64-QAM
Frame duration	10 ms
SSTTG/SSRTG	1 OFDM symbol
Initial ranging interval	5 OFDM symbols
Bandwidth request interval	5 OFDM symbols
Simulation time	1 min

that the user throughput, overhead, and latency increase as the traffic load is augmented for all the schemes. Due to the effect of direct communications conducted among SSs, the performance of proposed APC approaches outperform that of the conventional scheme under various traffic loads. Noted that the latency for the conventional mechanism consists of queuing and transmission latency; while additional latency for direct link setup is considered in the APC approaches. It is observed that comparably lower latency can be obtained via the proposed APC approaches than the conventional scheme since the direct link setup is conducted along with the original data transmission. Comparing between the APC-TO and APC-EO mechanisms, relatively better performance is observed in the APC-TO scheme. This can be attributed to the reason that the EO constraint is considered more stringent compared to the TO constraint in terms of the criterion for direct transmission. Therefore, less pairs of SSs are allowed to conduct the direct communication while the APC-EO approach is exploited, which results in relatively lower performance in comparison with the APC-TO scheme.

For each APC approach, it is observed that conducting direct transmissions in UL subframes has better performance than that in DL subframes, which can be contributed to the potential inter-cell interference resulted from the transmissions. In the case that direct communication is utilized by a pair of SSs in DL subframes, the SSs conducting conventional communications in the neighboring cells will be interfered by this pair of SSs since those neighboring SSs are served as receivers for DL transmissions. In order to confront the increased interference and to ensure successful packet transmission, lower-level of MCSs will be adopted by the SSs with conventional communication in the neighboring cells. Consequently, the entire system performance is decreased; while the communication overhead and latency will be increased. In the UL case, on the other hand, all the SSs adopting the conventional scheme are assigned as transmitters and the BS will be the only receiver for each cell. The interference from the direct communication pair to the neighboring SSs will be comparably lower than that in the DL case. Therefore, compared to the DL case, higher user throughput with lower overhead and latency can be obtained by assigning direct transmission in UL subframe.

In the case of lower traffic load, the performance gain is not obvious since the total available bandwidth is sufficient to support packet transmission for both the conventional and direct schemes. Therefore, as can be seen in Fig. 10, all the compared schemes have the same user throughput under traffic load $\lambda = 0.01$. However, under low traffic loads, the benefits resulted from direct communication can still be observed in terms of overhead and latency. Slightly lower overhead and latency are acquired by the proposed

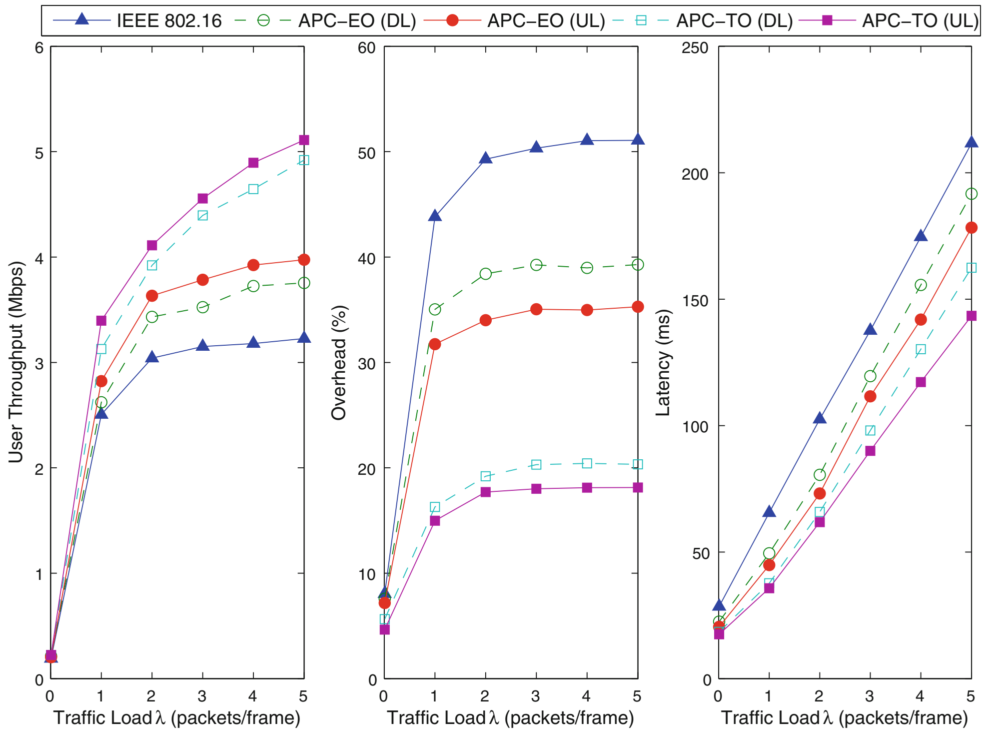

Fig. 10 Performance comparison: user throughput, overhead, and latency versus traffic load (λ)

APC approaches in comparison with the conventional scheme under the situations with low traffic loads.

Performance comparisons with an increasing number of intra-cell traffic ranging from 0 to 400 is shown in Fig. 11. The packet arrival process of each flow is assumed to follow a Poisson process with rate $\lambda = 2$ in unit of packet per frame. As can be expected that the user throughput, overhead, and latency increase as the number of intra-cell traffic flows is enlarged. The performance of proposed APC approaches outperform that of the conventional scheme. In the conventional scheme, the intra-cell traffic is required to be forwarded by the BS. Consequently, more than twice of the communication bandwidth is necessitate for the packet transmission. By adopting the proposed APC approaches, the intra-cell traffic can be directly transmitted from the source to the destination, which resulted in conserved bandwidth. Consequently, relative higher user throughput, lower overhead, and lower latency are acquired in the APC approaches. Similarly, the APC-TO approach outperforms the APC-EO scheme; meanwhile, arrangement of direct communications in UL subframes outperforms that in DL subframes for each APC approach.

Figure 12 depicts the influence from the percentage of inter-cell traffic flows to the performance of these three schemes. In this comparison, 200 traffic flows with the same packet arrival rate $\lambda = 2$ are considered. It can be seen that the user throughput decreases as the percentage of intra-cell traffic flows is increased for all the schemes, wherein the conventional scheme has the worst throughput performance. This can be attributed to the reason that the intra-cell traffic is required to be forwarded by the BS in the conventional scheme. However, there can be opportunities for the proposed APC approaches to conduct direct communications among SSs. On the other hand, due to the same reason, the overhead and the latency for all the schemes increase as the percentage of intra-cell traffic flows is enlarged. Similarly, the APC-TO approach outperforms the APC-EO scheme, and relative better performance is resulted from direct communications that are conducted in UL subframe comparing with that in DL subframes for each APC scheme. The merits of proposed APC approach can therefore be observed.

6 Conclusion

In this paper, a flexible and contention-free adaptive point-to-point communication (APC) approach is proposed. A comprehensive architectural design associated with the extended frame structures for the proposed APC approach is developed to be backward-compatible with the IEEE 802.16 standard. The proposed scheme arranges specific time intervals from the BS to achieve point-to-point direct communication among the SSs while they are adjacent with each others. Both the channel conditions and the relative locations between the BS and the SSs are utilized

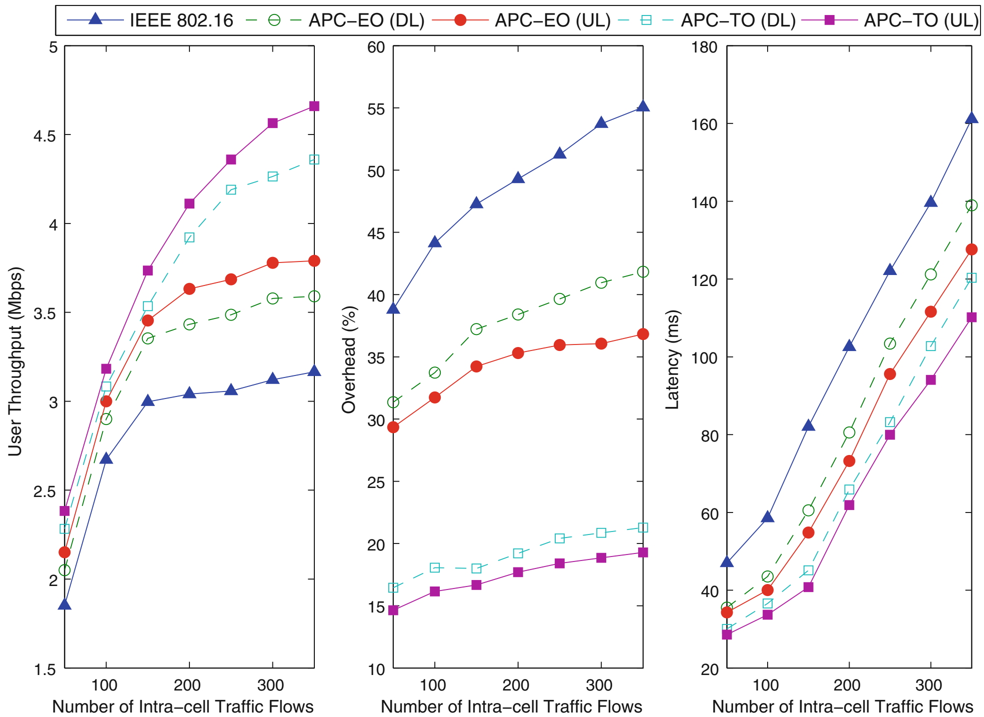

Fig. 11 Performance comparison: user throughput, overhead, and latency versus number of intra-cell traffic flows ($\lambda = 2$)

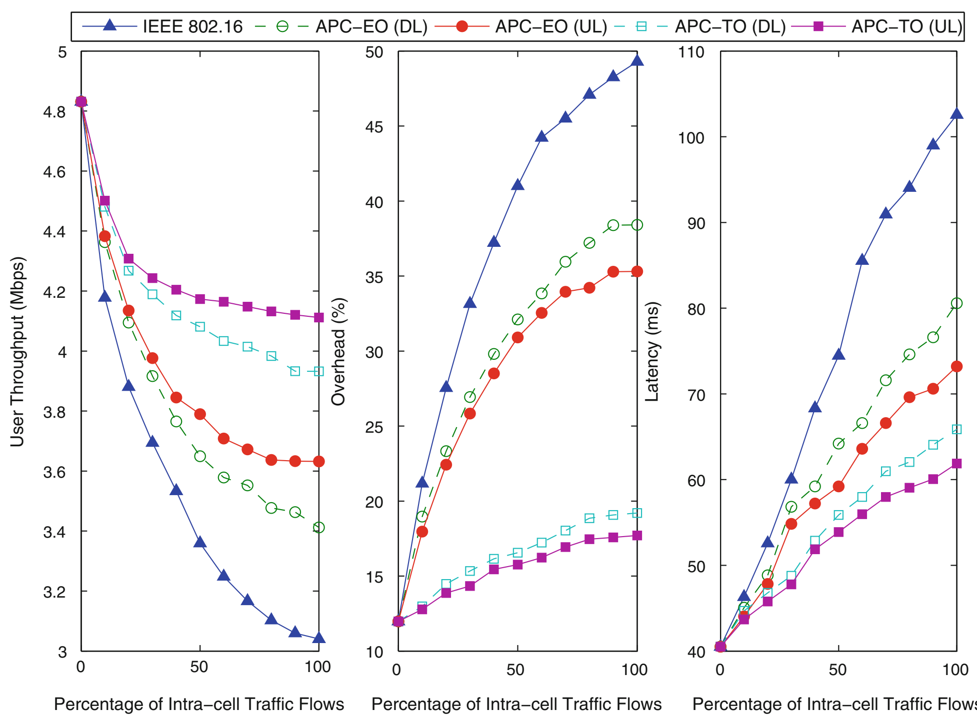

Fig. 12 Performance comparison: user throughput, overhead, and latency versus percentage of intra-cell traffic flows ($\lambda = 2$)

as constraints to determine if the APC approach should be adopted. Based on both the analytical and simulation results, it is observed that the proposed APC approach can outperform the conventional IEEE 802.16 transmission mechanism under different network scenarios.

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