Resource Reservation Schemes for IEEE 802.11-Based Wireless Networks: A Survey

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***Abstract*—IEEE 802.11-based wireless technology is widely applied in many areas, supporting communications where wired devices are not available. However, providing satisfactory QoS is still a challenging topic in 802.11-based wireless networks because of the problems such as error-prone wireless channel condition, power consumption, short of centralised facility, mobility as well as channel contention. For addressing these issues, one feasible solution can be to implement resource reservation for the sessions that require QoS assurances. The responsibility of resource reservation scheme is to make sure that QoS-sensitive session can get sufficient bandwidth to sustain their high performance. Difficulties are already identified for designing resource reservation schemes in both network and MAC layers. However, there is no profound investigation outcome for this kind of QoS mechanism. Therefore, in this paper, we intend to produce a comprehensive survey of resource reservation approaches for IEEE 802.11-based wireless networks. The associated research works are summarized and also classified. Moreover, both the drawbacks and the merits of each kind of resource reservation scheme are highlighted.**

***Index Terms*—quality of service, IEEE 802.11, resource reservation;**

I. INTRODUCTION

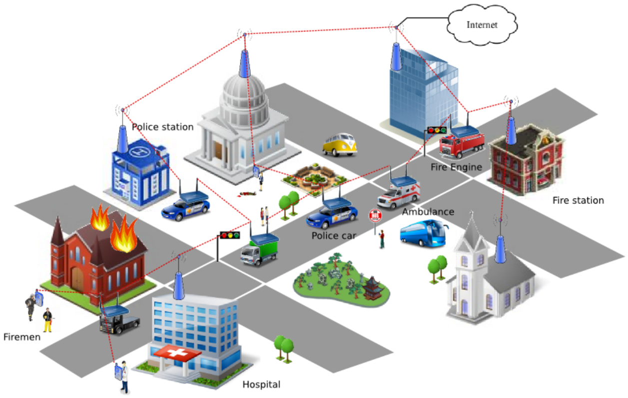

Fig. 1. An example of "smart city" use case

Nowadays, IEEE 802.11-based [1] wireless communication technology has enabled a mass market. It can be employed in various areas such as Wi-Fi hot spots, city wide mesh networks, intelligent transport systems, etc. The most personal communication devices such as laptop computers as well as mobile phones are equipped with 802.11a/b/g/n adapter or 802.11-compliant entities. The IEEE 802.11 techniques can be employed in large-scale wireless sensor networks utilized in the scenarios such as ecological sensing, structural monitoring, smart spaces, and remote surveillance system [2]. The IEEE 802.11-based wireless mesh networking technique can also make multi-hop communication in large-scale wireless networks practical, providing a solution to metropolitan area network [3], [4], as for example 'smart city' shown in Fig. 1. It can help overcome the limitations of a conventional broadband wireless access network, where all the communications have to traverse through a centralised station. Although multi-hop communication in wireless mesh networks can be implemented on top of other standards such as IEEE 802.16, the cheap availability of 802.11 hardware makes a major contribution to its rapid growth [5]. The recent amendment IEEE 802.11p standard can support vehicle-to-vehicle and vehicle-to-infrastructure communications, which are critical for an intelligent transport system. Despite of the extensive applications, there are still lots of issues that pose difficulties in providing Quality of Service (QoS) in IEEE 802.11-based wireless networks.

Since applications are grouped and/or identified into different priorities by the network layer protocol (for example by IP), how to provide enhanced performance for QoS sensitive sessions such as video and voice has become an interesting and challenging topic. The QoS provisioning can be implemented by many ways such as guaranteeing throughput, reducing end-to-end delay and mitigating packet loss ratio. The key elements that can be involved in a QoS assurance system are QoS-aware routing, traffic policing, admission control, QoS Medium Access Control (MAC) scheduling [6], etc.

In this paper, we intend to focus on one of the most effective solutions among the field of QoS provisioning, that is, Resource Reservation (RR) scheme. The purpose of RR is to provide QoS for high-priority sessions through reserving resources at all intermediate nodes along the route from the source to the destination [7]. In general, the objective of RR is to ensure that the high-priority sessions such as multimedia applications obtain sufficient bandwidth throughout their transmission time so as to guarantee their fundamental QoS requirements.

One of the issues on proposing RR scheme is how to find out available resources along a route. A proper QoS-aware routing scheme can serve the purpose [8]. Basically, QoS routing is capable of searching and erecting a route from the source to the destination that can suffice the QoS demands of Real-Time Sessions (RTSNs) [9]. In fact, some QoS routing schemes can be regarded as RR mechanisms for the reason that they identify the routes with sufficient bandwidth and make the newly arrived RTSNs utilize the resources before other sessions pumping into the network. In wired networks, links enjoy disjoint bandwidth which results in settled capacities and only sessions going through the same link contend for the bandwidth with each other. However, in wireless communication environment, bandwidth is shared among neighbouring links under the same channel. The attainable QoS of a session along a route depends on not only the resource availability of the nodes along its route but also the bandwidth of neighbouring nodes within the interference range of the route. Therefore, before making the decision of RR, negotiation between the reserved route and its interfering neighbours must be implemented so as to protect the existing transmissions near the tagged route. On the other hand, for collecting or disseminating resource state information, MAC or routing packets may need to piggyback additional message. An alternative way is to implement a signalling process for establishing the reserved transmission route.

There are several approaches that can implement RR. These solutions are QoS routing, MAC scheduling mechanism and admission control. The QoS MAC scheduling mechanism can provide QoS improvement to high priority sessions by implementing service differentiation on bandwidth reservation. The bandwidth reservation can be achieved by assigning more chances of channel access or directly allocating exclusive bandwidth for the sessions with QoS requirements. In centralised networks, resource scheduling is conducted by central controlling entities such as Access Point (AP) and base station. Since such centralised devices are not available in certain cases, distributed scheduling mechanism is expected to be implemented. It can be achieved by utilizing explicit signalling or QoS routing before executing RR in order to figure out the residual resources which can be reserved for the newly arrived RTSN and then negotiate the reservation with the nodes involved. If a RTSN arrives at a node which has no route to the destination, the QoS routing can be activated to identify the route with sufficient resources. If the node finds out that the route has already been set up, reservation control message carried by signalling or piggyback mechanism can be used to check the availability of the resources along the route. Following this, resource state information of reservation can be transferred to each node along the route as well as the neighbouring nodes. Based on the information gathered from all the nodes involved, source node is able to find out whether the RR is feasible. On the other hand, Admission Control (AC) can cooperate with MAC scheduling mechanisms or QoS routing schemes, protecting existing guaranteed RTSNs from being interrupted by additional RTSNs which pump into the networks when no adequate resources is available. With the support of AC, available resources can be detected by certain nodes during route discovery process and according to the usable bandwidth and the QoS requirements of the new sessions, decision can be made on either admitting or rejecting new sessions.

To date, there are several surveys proposed for investigating the QoS issues [6], [8], [10]–[12] regarding 802.11-based technique. The AC algorithms for mobile ad-hoc networks are discussed in [6] and QoS routing schemes are reviewed in [8], [13]. As a primary layer for providing QoS, the literature survey on the topic of MAC layer is also undertaken in [11], [12]. But none of them specifically focus on RR point of view in 802.11-based networks. Since the 802.11 wireless access technology is essential for the next generation telecommunications and RR as an effective way to provide QoS can play a very important role, it is noteworthy to investigate the state-of-art for RR schemes and point out how they can be further improved.

In this paper, we only concern about single-channel 802.11-based networks. This is because single-channel 802.11-based networks are applied more pervasive than multi-channel based networks. Also, only unicast schemes are included and the multicast is not the focus.

The rest of the paper is organized as follows. Section II discusses the existing MAC channel access schemes in IEEE 802.11 standard and points out their shortages. Section III presents the challenges of proposing RR schemes in IEEE 802.11-based wireless networks, followed by Section IV which specifies the key elements included in RR schemes. In Section V, the considerations of designing RR schemes are involved while the design trade-offs are discussed in Section VI. Section VII discusses the classification of RR schemes and describes the existing RR schemes, highlights their main features. Section VIII specifies the trends and progress of RR schemes. Finally, Section IX concludes this paper.

II. IEEE 802.11 MAC STANDARD OVERVIEW

The first IEEE 802.11 standard regarding MAC layer specification was issued in 1997 [14]. Since QoS provisioning is not taken into account in the legacy 802.11 MAC channel access technology, in order to support QoS, IEEE 802.11e was standardised. Considering that MAC scheduling mechanism is one of the crucial elements for performing effective RR which is the key focus of this paper, the characters of the existing MAC schemes in the standard are presented in detail.

A. Distributed MAC channel access: DCF and EDCA

The initial IEEE 802.11 standard defines a contention-based channel access mechanism known as Distributed Coordination Function (DCF). In DCF, nodes contend for the chance of channel access by means of Carrier Sense Multiple Access mechanism with Collision Avoidance (CSMA/CA). In order to avoid collisions, DCF utilizes a Binary Exponential Back-off (BEB) and a deferral mechanisms to differentiate the transmission start time of each node. On the other hand, by using channel sensing, nodes overhearing the transmissions from neighbouring nodes will set up the Network Allocation Vector (NAV) accordingly in order to alleviate the potential conflicts.

In order to obtain the chance of data transmission, a node needs to experience a back-off procedure. A back-off counter specifies the number of back-off slots the node has to defer before accessing the channel. The value of back-off counter is uniformly selected in the range of $[0, CW-1]$. The CW stands for the contention window size. At the first transmission attempt, CW is set to W_0 which is the minimum

TABLE I
THE DEFAULT EDCA PARAMETERS

AC	CWmin	CWmax	AIFSN	TXOPlimit (ms)
AC_VI	7	15	2	3.264
AC_VO	15	31	2	6.016
AC_BE	31	1023	3	0
AC_BK	31	1023	7	0

contention window. It is doubled whenever an unsuccessful transmission is detected. The CW stops increasing when it reaches the maximum value, $CW_{max} = 2^m W_0$. Note that m is the doubling limit. The contention window is maintained at CW_{max} for the subsequent transmission attempts. If the amount of retransmissions exceeds a retry limit M, the packet will be discarded and the CW is reset to the minimum value. The CW is recovered to the minimum value every time after a successful data transmission. Before back-off is activated, the node senses the channel which is idle for a duration called DCF InterFrame Space (DIFS). If the channel becomes busy when the back-off is counting, the process is frozen until the detected transmission finishes. Back-off is re-activated after sensing the channel for another idle DIFS. A node initiates its data transmission once its back-off time-outs.

DCF does not explicitly support QoS to specific traffic sessions with QoS requirements, such as RTSNs. Equipped with the identical back-off and deferral parameters, non QoS sensitive sessions will deprive bandwidth from RTSNs so that their QoS demands can not be sufficed [15]–[17]. On the other hand, collisions will dramatically increase under high traffic loads and high density of nodes within a contending region [18].

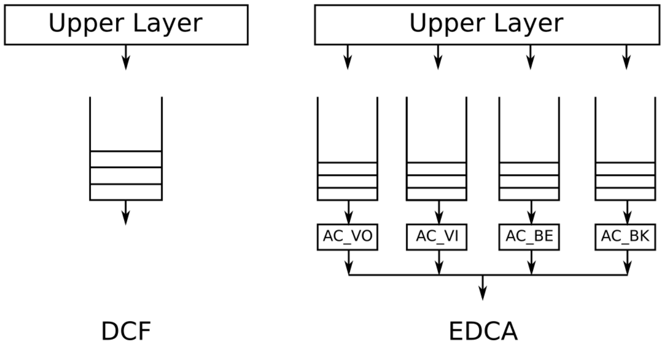

Fig. 2. DCF and EDCA

In order to support QoS for legacy DCF, IEEE 802.11e has standardized an Enhanced Distributed Channel Access (EDCA) mechanism. It can provide prioritized QoS by differentiating the parameters of deferral and back-off for different types of sessions. Different from DCF which possesses only one queue to buffer all types of packets, EDCA implements 4 logical queues (i.e. access categories) for the prioritized applications (i.e. high priority session). Tab. I shows the default parameters for different types of applications in EDCA. As shown in Fig. 2, by using shorter back-off and deferral durations, RTSNs tend to obtain more chances of channel access than the other types of sessions. In case internal collision happens when more than one access categories finish back-off counting simultaneously, the access category with the higher priority will secure the opportunity for accessing the channel while the other contending access categories restart their back-off processes.

Although EDCA provides differentiated services toward different types of sessions, RTSNs still suffer from degraded performance under high traffic load and high density of contending nodes. This is because EDCA still follows the contention-based channel access which will result in collision. Meanwhile, Non-Real-Time Sessions (NRTSNs) can hardly get the opportunity to access the channel if it attempts to transmit with RTSNs with high traffic loads [19]. This will cause the fairness issue. In addition, EDCA can not effectively deal with the QoS issues in multi-hop wireless communication because of the problems such as hidden terminal and interference [10]. Following the manner of random channel access, it still can not accurately take control over the transmission attempts of RTSNs due to the inherent deferral and back-off.

B. Centralised MAC channel access: PCF and HCCA

Different from the distributed channel access, in Point Coordination Function (PCF), all the nodes communicate with each other via a Point Coordinator (PC) which usually resides in the AP. As the central coordinator, the PC splits the channel airtime into super-frames containing Contention-Free Period (CFP) and controlled access period. Polling-based mechanism is employed in the CFP and the controlled access period still operates under contention-based environment. In the CFP, each node except PC initially sets NAV as the maximum duration (CFPMaxDuration) at the start of each CFP and the NAV is reset if the node receives CF-End or CF-End+ACK frame from the PC when the CFP finishes. Nodes can only transmit their data once being polled by the PC. After broadcasting beacon frame at the beginning of CFP, the PC waits for a Short InterFrame Space (SIFS) and starts transmitting CF-Poll frame. Polled by the PC, the corresponding CF-Pollable node transmits data without Request To Send (RTS)/Clear To Send (CTS) control handshaking after a SIFS. Fig. 3 shows an example of contention-free data transmission in PCF.

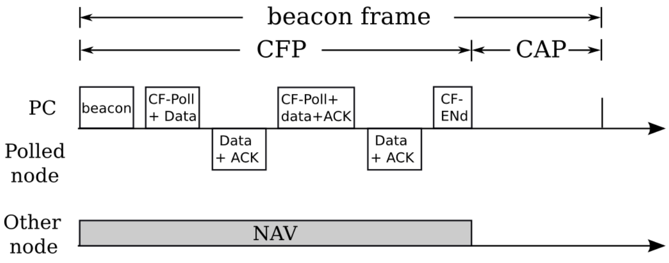

Fig. 3. Contention-free transmission in PCF

PCF introduces contention-free transmission in the CFP. However, there are still several problems which pose difficulties in providing QoS. Firstly, PCF does not support any prioritized differentiation toward sessions with distinct priorities. Albeit reserved bandwidth can be provided in the

CFP, the occupied resources of the polled nodes can not be predicted. The contention-free transmission time for each node is not bounded so that fairness issue may take place [20]. In the case of high traffic load, there is no admission control available for rejecting traffics so as to support QoS for the existing traffics [5]. In addition, the un-guaranteed transmission of (re)association frame for all the nodes may give rise to an additional delay [21].

In order to deal with some of the QoS issues in PCF, HCF Controlled Channel Access (HCCA) is proposed in IEEE 802.11e standard. Through a new coordination function known as Hybrid Coordination Function (HCF), HCCA utilizes Traffic Specification (TSPEC) that includes the QoS requirements of RTSNs. Before a RTSN is served by HCCA, the TSPEC needs to be negotiated between the node and a Hybrid Coordinator (HC). The TSPEC contains the information of RTSNs such as mean data rate, maximum Service Interval (SI), nominal MAC Service Data Unit (MSDU) size, delay bound, minimum physical layer rate, etc. Once the negotiation is successfully achieved, the session is admitted and dedicated Transmission Opportunity (TXOP) will be allocated to it in each polling cycle. A scheduling scheme will take charge in deciding the size of TXOP for each admitted RTSN. During the controlled access period, the HC controls the channel access for data transmission and polls each admitted session to proceed with data transmission in its dedicated TXOP.

HCCA implements several improvements for PCF, for instance, the definition of TXOP which standardizes the maximum duration a node can be allocated for data transmission during the CFP. By defining TXOP, the fairness toward non-AP nodes in a Basic Service Set (BSS) can be achieved. In addition, HC is entitled to detect the queue size of each non-AP node via an additional message embedded in QoS data frame. It is helpful for the design of dynamic RR scheme based on HCCA [22].

TABLE II
IEEE 802.11 MAC CHANNEL ACCESS METHODS COMPARISON

Scheme	DCF	EDCA	PCF	HCCA
Access method	Contention	Contention	Hybrid	Hybrid
Access category	Distributed	Distributed	Centralised	Centralised
QoS support	No QoS support	Prioritized QoS with service differentiation	RR but no explicit QoS support	Guaranteed QoS with RR

The two centralised schemes have inherently implemented RR for high-priority sessions and the other types of sessions can gain the opportunities of channel access in the Contention Access Period (CAP) under contention-based environment. Tab. II shows the comparison with all the MAC channel access methods in IEEE 802.11 standard. Although RR can be achieved by using centralised MAC schemes, some problems are still manifested in QoS guaranteeing. For instance, despite of QoS improvement achieved by HCCA, it still can not address the problem of polling overhead introduced prior to data transmission of a node. This will significantly affect the network performance. Furthermore, in an infrastructure-based wireless network, all the data transmissions will be relayed by centralised coordinators. Peer-to-peer transmission among the nodes within a BSS is inhibited. This will also affect the network performance if the controllers become disabled [23]. Moreover, collisions caused by inter-cell interference among the nodes which are covered by multiple APs is still a big issue [24]. On the other hand, the scalability becomes a problem for centralised schemes in a large-scale of network with dynamic traffic pattern. Eventually, implementation complexity prevents the centralised schemes from widespread application [25].

In infrastructure-less networks, centralised utilities are not available. Therefore, many research works have been concentrated on the design of distributed RR schemes based on DCF and EDCA. It has been proved that under certain level of non-saturated condition, even DCF can provide stringent QoS assurance toward multimedia applications [26]. However, when the channel busyness ratio increases, the network performance will be drastically degraded because of collisions [27]. Implementing RR can make high-priority sessions use the bandwidth with low collision probability or even no collision. Thus, their performance can be guaranteed.

III. CHALLENGES FOR THE RR SCHEMES

Implementing RR for providing QoS to high-priority sessions in IEEE 802.11-based wireless networks is feasible. However, there are several issues that pose difficulties for the protocol design in IEEE 802.11-based wireless networks. Most of the challenges are similar to the problems existed in the field of QoS provisioning in 802.11-based networks. However, the impact is different in the context of RR schemes and thus they are discussed in this section.

1) ***Short of centralised control:*** As mentioned in Section II-B, RR can be inherently achieved by polling-based schemes. However, distributed topology is applied more pervasively than centralised one, especially in some occasions that central controllers can not be erected due to environmental constraint or financial limitation. Challenges come up along with the efforts for implementing RR in distributed networks. There is no centralised node taking responsibility for allocating dedicated resources and disseminating reservation control information. As a result, schemes such as explicit signalling, piggyback and control frame extension are required to be devised in order to transfer and update the state information of reservation in a distributed manner. This causes additional overhead and thus degrades the performance of sessions sharing the local channel resources.

2) ***Error-prone wireless channels:*** As mentioned before, reservation control information becomes a necessity for making RR. The control message for setting up RR has to be received properly by the nodes sharing and/or interfering the channel along the route so that the RR can be successfully achieved. However, under unreliable wireless channel caused by thermal noise and multi-path fading effects, reservation control message may not be properly decoded. In this case, other than lapsed QoS, reservation control information may not be able to be diffused to certain nodes which need to align to the reservation schedule. This will lead to additional interference and exacerbate the reserved transmissions.

*3) **Medium contention**:* In the case of IEEE 802.11-based single-channel environment, the problems such as channel contention and interference often occur. These issues significantly affect the available channel capacity for a node [6]. In order to make RR, a node must know all the traffic sessions traversing through its contending region because they may interfere with its own transmission. On the other hand, if reserved bandwidth has been already announced by the neighbouring nodes, the corresponding node should align to the RR scheme and avoid transmission during the reservation periods of the other nodes.

For solving the issue of collision at receivers, a Carrier-Sensing threshold (*CS-thresh*) is utilized in 802.11-compliant senders, enabling these devices to properly receive packets despite of detecting interfering signals at a much lower power. If a sender senses a signal whose power is higher than CS-thresh, it regards the channel state as busy. The CS-thresh produces a particular Carrier Sensing (CS) range[1] depending on the transmission power as well as the signal propagation properties. In order to reduce the collision probability, the CS-thresh can be decreased so that the CS range is extended accordingly. However, the side effect is the sacrifice of the efficiency of spatial reuse. The efficiency of spatial reuse determines the number of possible concurrent transmissions in the network. It also has great impact on network capacity. Increasing the CS-thresh can result in shrunk coverage of CS range and higher efficiency of spatial reuse. However, the collision probability will increase, which leads to the wastage of bandwidth and incurs the retransmissions that can further result in route failure once the retransmission count limit exceeds the retransmission threshold. Consequently, the balance between the efficiency of spatial reuse and the level of collision needs to be prudently handled [28].

Apart from the above issues, shared wireless medium can also result in mutual contention and interference among the nodes along a route through which data packets are forwarded. This phenomenon will be described in Section V.

*4) **Finite resource availability**:* Due to the wireless properties, resources such as bandwidth and battery life are scarce in IEEE 802.11-based wireless networks. This poses challenges to the schemes which focus on QoS provisioning. For instance, limited bandwidth occupation leads to low physical transmission rate. Under this circumstance, sessions with high priorities need to get more time-slots for transmission in order to meet their QoS requirements. However, allocating additional resources for these sessions will result in less network capacity which is available for other sessions. On the other hand, if the limited battery life of a node is exhausted, the node would be disabled or enter a sleep mode. The multi-hop communication traversing this node has to trigger a re-routing process in order to find another feasible route leading to the destination. This will incur extra cost to the network capacity and directly degrade the network performance.

*5) **Node mobility**:* In some cases, nodes need to move from one place to another in a wireless network. Mobility of nodes can result in dynamic variation of network topologies. State information maintained in certain nodes will become inaccurate if they move out of transmission scope of other nodes. Thus, the reservation state information related to a route or a position is required to be updated so as to adapt to the node mobility. This will incur extra burden for the network and affect the performance of sessions.

IV. KEY ELEMENTS INVOLVED IN RR

According to the functionalities of different layers, RR can be implemented by either QoS-aware routing or QoS MAC scheduling scheme with the support of AC and QoS signalling for RR, as shown in Fig. 4. Other elements such as the rate and congestion controls at the transport layer can also be operated in a RR scheme, They can tune traffic volume in order to alleviate the issue of medium contention, but the transport layer issues are not the focus of this paper. This section discusses the key elements in RR schemes and specifies their functionalities.

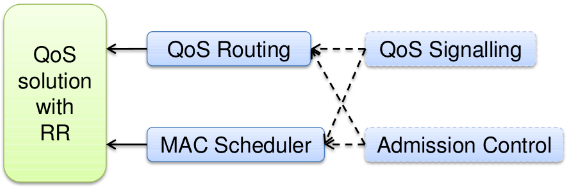

Fig. 4. Key elements involved in RR schemes

A. Routing Scheme

Routing scheme is responsible for searching a feasible route by which data packet can be relayed from the source to the destination. Since the neighbouring transmission links in wireless communication interfere with each other, available resources are varying according to the distribution of flows in the networks. Different from traditional routing scheme, QoS routing can optimize flow distribution in line with certain routing metrics such as achievable throughput, end-to-end delay and available bandwidth. In some cases, multiple routes can be identified for a RTSN and one of them is selected as the primary route for data transmission while others may become the backup routes in case of route failure. In most of the cases, RR in QoS routing is implemented after the destination confirms the route discovery. One of the key issues of routing scheme with RR is the accuracy of resource estimation. RTSNs can get guaranteed performance only if sufficient bandwidth can be ensured. Therefore, a good routing scheme with RR needs to identify a route with sufficient resources for RTSNs in order to meet their QoS requirements. On the other hand,

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[1] In general, CS range is larger than interference range [28]. Further detail about the relation between CS range and interference range can be referred in [29], [30].

control overhead incurred by routing needs to be constraint. Consequently, an effective solution should have accurate bandwidth estimation, minimum control overhead and it should be capable of adapting the change of network state.

Routing scheme with RR can incorporate with AC which can make the decision of accepting or rejecting new-coming sessions. With the support of AC, routing scheme with RR can decide to make a RTSN occupy bandwidth along a route with sufficient bandwidth. However, routing scheme can not make actual resource scheduling. Using routing schemes, resources reserved for a session may be interrupted because routing scheme can not control over the transmission attempts of interfering sessions. The information of channel contention can be obtained from MAC layer and can help routing scheme to implement RR decision more accurately. However, it still can not solve the collision issue.

B. QoS MAC Scheduling Mechanism

MAC scheduling mechanism is essential for managing bandwidth allocation and implementing service differentiation toward distinct types of sessions. It determines the efficiency of the bandwidth utilization in wireless channel. The collision avoidance can also be achieved via implementing an effective scheduling mechanism. This mainly depends on the way the state information of reservation is synchronized. The synchronization among nodes is very crucial for a RR scheme [7]. The fully synchronized channel access method is Time Division Multiple Access (TDMA). It can make global reservation information be known by all the nodes. Each node has its pre-scheduled time-slot to proceed data transmission and the resources appear periodically after a certain amount of time. In this way, RTSNs can obtain sufficient bandwidth for meeting their QoS requirements. However, achieving tight synchronization is very sophisticated. In addition, resource wastage will occur if network topology and resource demands are dynamically varying.

In the IEEE 802.11-based centralised networks, the channel access methods such as PCF and HCCA can be regarded as semi-synchronized schemes. Synchronization can be achieved during the CFP by the AP which disseminates polling frame so that the state information of reservation is informed by all the nodes within its transmission range. In the meantime, CAP operates in an asynchronous contention-based channel access manner. The synchronization in centralised schemes are mainly achieved by central controllers. Since they manage the scheduling within their own coverage, inter-cell interference occurs once two or multiple central devices locate within each other's range. In terms of the IEEE 802.11-based distributed wireless networks, there is no centralised device that can support synchronization among the nodes. Therefore, contention-based mechanism is applied among the nodes within contending region. Nodes can merely be temporarily synchronized with other nodes that reside within their transmission range by overhearing control or data message. Thus, collision happens frequently due to the interference from other nodes along a route or interfering nodes resides within the CS range. Thus, a good MAC scheduling mechanism with RR needs high level of synchronization for the state information of reservation while considering to overcome the implementation issue.

Another concern about MAC scheduling mechanism is how to reserve bandwidth for RTSNs in order to meet their specific QoS requirements. For example, video sessions desire to satisfy both throughput and delay demands while voice sessions, on the other hand, may only need to receive guaranteed delay but have loose throughput requirements. To assure different levels of QoS, RR needs to be adjusted accordingly. Beside that, the fairness toward other types of sessions (i.e. background and best-effort) also needs to be taken into account. These aspects are further discussed in Section V and VI. Consequently, the effectiveness of MAC scheduling mechanism with RR depends on the level of synchronized state information of reservation, level of QoS provisioning through RR, and the fairness toward other types of sessions.

As mentioned above, MAC scheduling mechanism with RR can implement actual scheduling and resource allocation, which can not be achieved by any other elements. It is the key element to solve the problem of channel contention and collision incurred by the issues such as interference and hidden terminal. To implement RR, the negotiation of reservation information is usually implemented by signalling, which can support synchronization for MAC scheduling mechanism. The signalling can either be integrated in routing process or explicitly be executed after a route is found. On the other hand, signalling message can also be piggybacked in control and data packet. This can help alleviate signalling overhead. MAC scheduling mechanism can also cooperate with AC in order to achieve highly non-interfering RR. This will be discussed in Section IV-C.

C. Admission Control

The purpose of AC is to accept new traffic sessions given that the performance of existing admitted sessions are not affected [6]. In a RR scheme, AC is crucial for protecting the QoS performance of sessions with dedicated resources and deciding the improvement of bandwidth efficiency. Since AC requires the collection of the available resource information before making decision, routing discovery process is always a good carrier for AC. Beside that, AC can also be implemented with the support of explicit signalling for RR. As for the AC in RR scheme, it can protect existing QoS sessions that have successfully reserved bandwidth while assessing whether there is sufficient resource available for newly arrived RTSNs. Bandwidth estimation is one of the key components in AC. Many metrics are introduced for estimating available bandwidth for AC. For instance, transmission budget and channel busyness ratio are two examples of the effective metrics which have been utilized and developed in many literatures [27], [31]–[34] while the probability of collision is deduced and applied in [35], [36]. With these information, AC can support MAC scheduling mechanism to make non-conflicting RR.

D. QoS Signalling for RR

Being a supportive process, QoS signalling is employed for negotiating resource state information. It usually commences after a route of a session is identified or can be part of routing process. In general, the signalling process for RR can be split into 3 parts: reservation establishment, reservation maintenance, and reservation termination. The reservation establishment is always initiated by the source node which sends the RR request to the destination. The reservation maintenance monitors a route with reserved bandwidth, repairs or reconfigures the established route if the reserved transmission is interrupted. The reservation termination releases the reserved bandwidth of terminated sessions. In centralised networks, the signalling is initialized by centralised controller which negotiates the RR with each source node. After the negotiation is successfully made, central device disseminates the up-to-date resource state information to all the nodes within its coverage via broadcasting a control message. In distributed networks, the negotiation can be implemented by sending a signalling message with RR information from the source to the nodes along the route that the session traverses. The signalling massage may require to be sensed by neighbouring nodes within the interference range of the QoS route in order to avoid interrupting the reserved transmission.

QoS signalling for RR causes additional overhead and affects the performance such as end-to-end delay. Therefore, the signalling overhead is desired to be minimized so as to reduce the impact on providing QoS assurance. Some solutions have been worked out for this purpose. For instance, signalling messages for RR can be piggybacked in control or data message [37], [38]. Another effective way is to build up master nodes in the distributed topology [39]. Akin to the centralised devices in infrastructure-based wireless networks, the master nodes can take control over the reservation information within its coverage. However, it is not as powerful as the centralised device but still helpful for alleviating signalling overhead.

V. RR SCHEME DESIGN CONSIDERATIONS

A. Network Resources

The network resources are critical and they are supposed to be managed optimally in a RR scheme in order to achieve guaranteed/enhanced QoS performance. Here we discuss some of the network resources from the RR perspective.

Channel capacity: As the most essential resource in a network, it determines the channel busyness ratio of each node and has great impact on other resources such as TXOP, route and buffer. Decreased channel capacity can result in longer TXOP for satisfying a RTSN's QoS demands, more buffer occupation, and less routes for a RTSN travelling from source to destination. In terms of the residual channel capacity, it is usually measured by bit per second (bps). Besides, fractions of channel idle time can also represent the residual capacity and it has been applied in many works, for example [40].

Transmission opportunity: TXOP defines the channel time allowed for the packets of a session to be transmitted. Some important parameters of a reserved TXOP include the service start time and TXOP duration. The determination of service start time depends on the condition of resource occupation of existing sessions as well as the effectiveness of the MAC scheduler. The TXOP duration is decided by either the MAC scheduler by default or an Admission Control Algorithm (ACA). In order to enhance QoS for RTSNs, the optimization of TXOPs for different nodes or RTSNs has been investigated in many works, for example [41], [42].

Route: Route for a RTSN is usually decided by a routing scheme which can be supported by ACA. Some of its properties such as the number of hops and the resource occupation of each node along the route directly affect the QoS performance of RTSNs traversing through the route. Thus, a QoS-aware routing is essentical for finding a QoS route with sufficient resources for a RTSN. A routing scheme can perform even better if the channel contention from MAC layer as well as the interference from the CS range can be taken into account. This will acquire a cross-layer design which is discussed in the next sub-section.

Buffer: Buffer decides the maximum queue size of a node and this parameter can have influence on queuing delay, which will then affect the total end-to-end delay performance. The size of occupied buffer is mainly dictated by the relationship between traffic demands and provided TXOP. If the reserved resource can not serve the traffic volume in a certain duration, occupied buffer will keep increasing and eventually lead to the buffer overflow. This will cause increased delay and packet loss.

B. Measuring and predicting network resources

Before making a RR, the amount of network resources needs to be discovered beforehand. Some of the existing works assume that network resources such as the channel idle time is always sufficient for reservation. However, this is not always the case especially when excessive sessions wish to obtain resources in a restricted area. To detect existing resources, there are three main methods which are listed below:

- Detect resource information during route discovery;
- Obtain resource information along a route by explicit signalling traversing from source to destination;
- Utilize the QoS experienced by the previously transmitted data packet to predict the remained resources;

The major solutions utilized by MAC layer RR scheme are the second and the third categories while the routing layer and cross-layer RR schemes mainly employ the first approach. The network resources can be measured or predicted in the following ways:

- Local residual channel idle time: According to specific channel capacity as well as the neighbouring traffics, local residual channel idle time can be measured as a kind of important resource for a node to reserve for its sessions. However, the measurement of local residual channel idle time for a node is closely associated with the measurable range. If the range covers the interference range which is virtually larger than transmission range, the detected resource information can be accurate, e.g. [43]. Otherwise, the resource will be either overestimated or underestimated e.g. [44]. The channel idle time can be represented by TXOP, idle back-off slots, etc.

- End-to-end route capacity: It can be measured by collecting the minimum local residual channel capacity of the nodes along the route, taking the inter- and intra-session contention into account e.g. [43]. Route capacity is usually measured following the first and second categories mentioned above. Many metrics are used to represent the route capacity, for example, channel idle time and channel busyness ratio which take the collision and channel contention into account. The accuracy of route capacity measurement also largely depends on whether the detected range is equal to the actual interference range.
- Probed QoS metrics: Network resources can be alternatively quantified by some measurable QoS metrics such as end-to-end delay, packet loss ratio, delay jitter, etc. It is usually measured by either sending a probe and collect its QoS performance as an indicator for the requesting session e.g. [44] or claiming the QoS performance of existing session traversing through the same route e.g. [45].

C. Network Resources Guaranteeing in RR scheme

Designing an efficient RR scheme for IEEE 802.11-based wireless networks is challenging. In general, several aspects need to be taken into account when proposing a RR scheme for QoS guaranteeing.

1) ***Alleviating collisions in reserved transmission****:* Unlike random access mechanism which makes data transmission happen at any time once the back-off time-outs, reserved transmissions are always pre-scheduled during the RR. Interference-free is the goal for these reserved transmissions so that the QoS guaranteeing for RTSNs can be achieved. In fact, several issues can pose interference in reserved transmissions. In general, signalling messages for establishing RR usually traverse through a route. Neighbouring nodes within the transmission range of the route can receive and decode the reservation control information by which they can subject to the reservation schedule. However, collision can still emerge in terms of the transmission commenced from a neighbouring node that resides outside the transmission range but within the interference range. This problem is referred to as inter-session interference. How to eliminate the collisions posed by the nodes that locate within the interference range is expected to be addressed in the RR scheme.

On the other hand, if a session traverses through a multi-hop route, nodes having overlapping interference range with other nodes across the route will suffer from unexpected collision. This attributes to the interference caused by other contending nodes along the route as well as the hidden terminal problem. This phenomenon is referred to as intra-session interference, which is anticipated to be addressed in the RR scheme.

2) ***Achieving high efficiency of spatial reuse****:* Spatial reuse indicates the scheduling of simultaneous data transmissions in the case that all the links share the same channel. Enhanced performance and network capacity can be achieved with high efficiency of spatial reuse. As shown in Fig. 5, collisions posed by hidden terminal problem happen in node 2 when node 1 starts transmitting right after node 2 senses the ongoing transmission in node 4. However, there is one exception that if the Signal to Interference-plus-Noise Ratio (SINR) exceeds a threshold *CPThreshold*, node 2 can still receive the packet from node 1 if the transmissions from node 1 and 4 occur simultaneously. Using specific scheduling mechanism, node 1 and 4 can transmit data simultaneously without collisions [46]. Similarly, it can be observed that the maximum bandwidth efficiency is achieved when node 1, 4 and 7 access the channel at the same time. There is no collision that occurs in the receiver 2, 5, 8 if SINR exceeds the *CPThreshold*. Therefore, data information can be decoded properly.

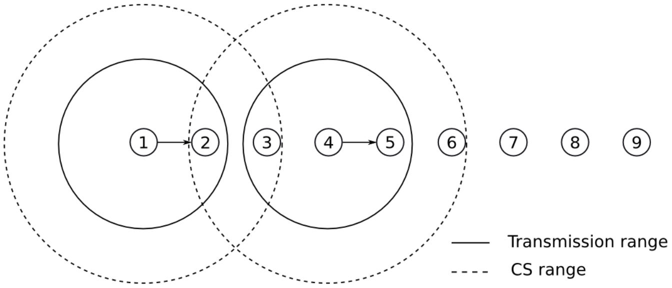

Fig. 5. Spatial reuse in multi-hop wireless communication

3) ***Achieving good scalability by reducing overhead****:* A RR scheme needs control message being propagated in order to claim the required resources from the nodes along a route or within a contending region. The scalability issue arises when the network scale becomes large. This issue is originally noticed in IntServ in which each session must make an individual RR via complex signalling [47]. Many later works focus on simpler service differentiation which is similar to DiffServ in order to alleviate the excessive control overhead, thus scaling well in large networks [48]. In general, the control overhead is mainly introduced by routing process, explicit signalling or piggyback mechanism. The control messages incurred by these processes must be limited so that they will not consume too much of network bandwidth [7]. However, since the network topology and the traffic status may change dynamically, additional control message needs to be disseminated in order to maintain or release the reserved bandwidth for RTSNs, which poses difficulties in achieving good scalability.

4) ***Providing fairness****:* A RR scheme is usually implemented for enhancing or guaranteeing the chances of channel access for RTSNs. In terms of the dedicated resources reserved for a RTSN, it is usually required to suffice the session's QoS demand. Since the amount of allocated resources is associated with the the session's data rate, RTSNs with high data rate will snatch excessive resources which may result in inadequate bandwidth for other sessions. On the other hand, once a session stops transmitting, its dedicated resources need to be released dynamically so that they can be reused by other sessions. Further, the fairness can also be reflected by other aspects. For instance, in polling-based mechanism, the fairness in the CFP usually indicates the equivalent chances for RTSNs to get polled and transmit data. In wireless multi-hop communication, the reservation implemented by routing scheme is expected to avoid reserving excessive resources along multiple routes for a single session in case that other sessions can not identify a feasible route with sufficient resources.

Normally, RR schemes aim to serve the sessions with stringent QoS requirements. Consequently, the more the QoS sessions exist, the less the available resources left in the networks. However, there are many other sessions with lower priorities (i.e. background and best-effort) wishing to obtain sustainable services. As a result, how to keep sufficient resources for supporting other traffic classes while making RR for RTSNs is another issue.

5) ***Cross-layer Design:*** As mentioned in IV, routing scheme can decide the end-to-end route and its underlying resources that can be scheduled by the MAC scheme, which can implement resource scheduling. A better way to achieve further enhancement of QoS is to devise schemes across the layers rather than single layer design, for example based on either MAC layer or routing layer. During the route discovery process, the routing functionality of the cross-layer scheme can find a QoS route for a RTSN to have sufficient resources available to be scheduled in line with MAC layer resource information. The MAC scheduling scheme will in turn benefit from the route information such as hop count in order to reserve bandwidth optimally. Another advantage of cross-layer deign scheme is that the transparency of information across the layers can alleviate additional signalling overhead implemented for information dissemination. For example, some fundamental resource detection for RR can be achieved during route discovery process so that the actual resource scheduling in MAC scheme does not need any further signalling for detecting resources. As an advanced way to produce guaranteed QoS, more efforts are expected to be made using cross-layer design.

6) ***Security:*** Traditionally, network security and QoS provisioning are considered independently as two separate research topics. However, recent works consider that security incurs overhead which will impact the overall QoS performance [49]. More security functionalities will result in more overheads for authentication which occupy additional network resources, leaving less available bandwidth for other RTSNs. In addition, the security overheads posed by encryption can cause additional delays for the corresponding sessions. Thus, the design of RR scheme is expected to be considered together with the impact of security.

VI. DESIGN TRADE-OFFS

Several trade-offs exist in the design of RR schemes. Some of them are similar with the trade-offs in QoS routing and QoS signalling scheme. But the issues and the impacts are different in the context of RR. Therefore, it is worthwhile to discuss them from the perspective of RR.

A. Reservation protection vs. Signalling overhead

As mentioned in Section IV, signalling is essential for supporting QoS MAC scheduling mechanism for the propagation of resource state information of reservation. The information of RR is carried by the signalling message which can inform the involved nodes of the latest information so as to protect the reserved transmission. However, since the signalling message shares the same channel with data packets, it directly affects the data transmission of sessions that traverse within its interference range. Without an effective interference avoidance mechanism, forwarding signalling messages may cause collisions during reserved transmission of existing RTSNs. In order to avoid interrupting the existing RTSNs with reserved bandwidth, signalling is expected to take place during non-reservation period. However, this will reduce available bandwidth for other newly arrived RTSNs to reserve. Consequently, signalling message needs to be minimized in order to provide more network bandwidth for data sessions. However, limited signalling may not be effective in informing all the involved nodes of the latest resource state information. If a node that resides along a route is not synchronized with the updated resource information, it may not be able to transmit data in its pre-scheduled duration. Also, unsynchronized nodes reside off-route but within the interference range may affect the QoS of sessions with dedicated resources.

B. Proactive vs. Reactive vs. Hybrid

In terms of routing schemes with RR, if the routes are discovered proactively, sessions can identify a route with sufficient resources upon arrival. In this case, they can select the route and reserve its resources immediately without any additional latency. Data can be transmitted from any source nodes because all the possible routes have been identified following proactive manner. Further, since applications have distinct QoS requirements that can be reflected by different metrics, a route is able to be computed from the routing table based on any QoS metric as long as the decided QoS states are always up-to-date [8]. The drawback of proactive routing scheme is the massive overhead introduced for maintaining the routes and updating the state information. This may deprive excessive network bandwidth and affect the QoS performance of RTSN with reserved bandwidth. In addition, the scalability issue makes the scheme perform poor when the number of nodes increases.

In contrast to the proactive routing scheme, the reactive routing scheme can avert the wastage of network bandwidth due to its on-demand route discovery which initiates only if a session requests. A node with RTSN usually triggers a route discovery process in order to identify a route with sufficient resources. However, reactive route discovery results in additional delay for RTSNs which attempt to reserve bandwidth. To balance the trade-off, a hybrid routing recovery scheme

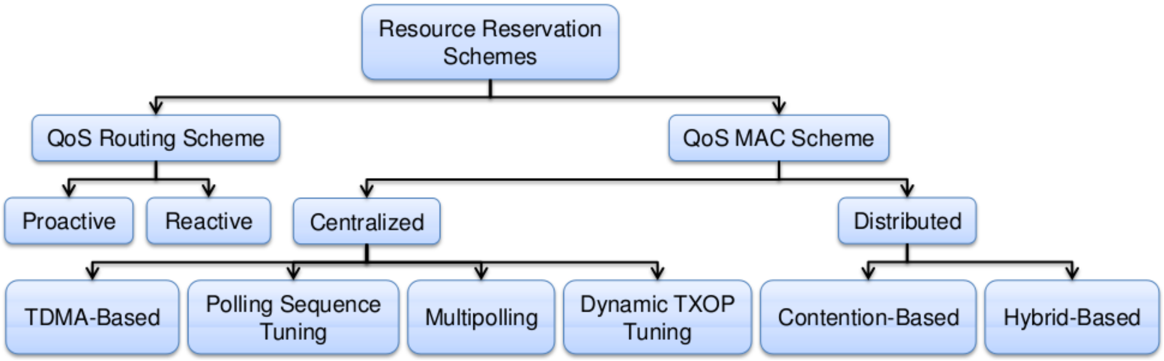

Fig. 6. A classification of resource reservation based schemes

is introduced. It generates zones within which each node performs the routing discovery process proactively. The inter-zone routing is implemented following the reactive manner. This can alleviate the scalability issue of proactive routing scheme. On the other hand, intra-zone routing can reduce the overhead that may introduce extra delay because the routing table has been established in advance.

C. Reservation capacity vs. Level of QoS provisioning

In order to provide guaranteed QoS for a RTSN, QoS requirement must be considered before attempting to reserve bandwidth for the RTSN. Obtaining guaranteed throughput and delay is needed for real-time applications. However, achieving guaranteed delay is much more difficult than guaranteeing throughput performance [50]. Guaranteed throughput can be derived as long as a scheduling mechanism can ensure that the measured time duration between successive instants in which the system is empty is limited. In contrast to throughput, guaranteed delay requires the expected duration mentioned above is low. Reserving dedicated bandwidth for a time critical session can serve the purpose. However, it has been indicated in [51], [52] that trade-off exists between reservation capacity and the level of QoS provisioning (i.e. delay). Here the reservation capacity indicates the amount of RTSNs that are allowed to reserve bandwidth. Reservation capacity enhances if QoS demands such as delay bound are not stringent. However, if the strict delay bound requires to be fulfilled, the amount of sessions that can secure resources are constraint, resulting in lower reservation capacity.

In some cases where Variable Bit Rate (VBR) sessions are involved, RR is complicated to implement for guaranteeing QoS requirements such as delay bound. Since the reference scheduler in IEEE 802.11 standard can merely allocate resource statically when a session initially arrives, it can not dynamically tune the volume of resources in line with the varying traffic load. Therefore, high packet loss ratio and delay occur if the allocated resources are not sufficient for a RTSN. On the other hand, statically reserving excessive resources for sessions with variable bit rates or low bit rates without any resource sharing scheme will result in wastage of bandwidth and the degradation of reservation capacity [53]. To deal with this problem, several schemes are proposed for implementing dynamic RR for VBR sessions according to their varying traffic loads. However, dynamic RR for VBR sessions will cause inaccurate information of available bandwidth for other sessions, posing difficulties for them to implement RR. The detail will be explained in Section VII-B1b.

VII. RESOURCE RESERVATION SCHEMES AND THEIR CLASSIFICATION

In general, RR schemes can be categorized in many ways. For instance, from the perspective of resource utilization, RR schemes can be classified into soft RR and hard RR. In the case of hard RR schemes, reserved bandwidth is supposed to be utilized only by its dedicated sessions and the resources are not allowed to be reused by other sessions unless they are released by their owners. On the other hand, if the reserved bandwidth is allowed to be shared by other sessions, this reservation mode is referred to as soft RR.

In addition, RR can also be classified into isochronous RR and asynchronous RR. In isochronous RR schemes, reservation period is well-synchronized by all the nodes within the network. In this case, allocated resources will be utilized under contention-free environment. In terms of asynchronous RR schemes, reservation is usually implemented under contention-based environment. Due to the un-synchronized nature of reservation schedule, exclusive bandwidth may be interfered or utilized by other nodes that reside within the interference range. Apparently, isochronous RR can provide better QoS than asynchronous RR because the reserved bandwidth is exclusively utilized by the sessions or nodes without any collisions or interference. However, some isochronous RR schemes need tight synchronization which is difficult to be implemented in distributed wireless environment. In contrast to isochronous RR schemes, asynchronous RR schemes can perform with less control overhead.

In this paper, the classification is made according to in which ISO layer the RR scheme is implemented. As mentioned before, RR schemes can be implemented via QoS-aware routing schemes or MAC scheduling mechanisms. The QoS routing with RR can be further divided into proactive and reactive schemes. MAC RR schemes can be generally categorized into centralised and distributed RR schemes, as shown in Fig. 6. Different kinds of solutions have been proposed for achieving or improving RR at the MAC layer. Details are discussed in Section VII-B1 and VII-B2.

A. QoS-Aware Routing Schemes with RR

The design of routing schemes becomes a challenging topic since the mobility function of nodes is introduced in IEEE 802.11-based wireless networks. The conventional routing schemes such as Ad-hoc On-Demand Distance Vector routing (AODV) [54], Dynamic Source Routing (DSR) [55] and Destination-Sequenced Distance Vector routing (DSDV) [56] are only designed for identifying feasible or shortest routes without detecting the network resources. Thus, they can not explicitly support QoS [57]. Since bandwidth is shared by the nodes within neighbouring links in wireless communication, if excessive sessions are determined to go through overlapping interference routes, collision will increase dramatically, which leads to degraded network performance.

Different from those schemes, QoS-aware routing schemes entail to exploit routes that can provide QoS for sessions and some of the mechanisms employ RR for high-priority sessions. In general, a QoS routing scheme with RR consists of a resource estimation process and a RR process. The bandwidth estimation is usually implemented during route discovery process while the RR is made after the route with sufficient resources is identified.

1) ***Proactive QoS routing schemes:*** In proactive schemes, route discovery usually takes place and completes before the arrival of traffic sessions. Available resources can be detected in advance during the proactive routing process and the related information can be updated in the routing table. This can lead to RR among multiple viable routes for a RTSN. For instance, a distributed ticket-based QoS routing scheme [58] employs redundancy of RR. Multiple routes can be reserved and only one of them is chosen as the primary route. A secondary route will be selected if the primary route can not meet the QoS requirements because of link failure or insufficient resources. Since hard reserved bandwidth is not allowed to be used by other sessions, the wastage of network bandwidth will be incurred. In contrast to the ticket-based scheme which tends to waste the redundant route resources, an Interference-Aware QoS Optimized Link State Routing (IQOLSR) scheme [40] utilizes a soft/hard reservation switching mechanism. The temporarily reserved bandwidth is allowed to be used by other sessions but the resources are forbidden to be reserved any more unless the reservation is waived. Upon the receipt of a reply regarding RR confirmation from the destination, the corresponding node will replace the state of soft reservation with hard reservation. Meanwhile, sessions which temporarily utilize the soft reserved bandwidth have to release the resources to the reservation owner. By doing this, one session can only pre-reserve resources but not exclusively occupy them until the hard reservation is confirmed. However, if a RTSN secures the bandwidth which is pre-reserved by another session, its QoS will be deteriorated once the hard reservation is confirmed because it has to release the bandwidth and be forced to find new resources that may not be available.

Common advantages and disadvantages: Proactive scheme can alleviate the impact of latency caused by routing process. Data can be transmitted from any source nodes because all the possible routes have been identified following proactive manner. However, they suffer from the overhead incurred for maintaining route and updating resource state information. On the other hand, proactive schemes usually make redundant RR for a session. This makes negative effect in terms of bandwidth efficiency and QoS provisioning. When network size increases, the routing table maintained by proactive schemes will grow significantly. This will block data transmission and cause overly congested channel [66].

2) ***Reactive QoS routing schemes:*** In reactive schemes, RR usually implements via route discovery and confirmation processes after a session arrives. For instance, in [60], an Adaptive Dispersive QoS Routing (ADQR) scheme utilizes route discovery process to find out available route for reservation. Since multiple routes can be found during route discovery process, source node selects the one with the highest priority and then implements RR by sending a signalling message. Another example is Partial Bandwidth Reservation Scheme (PBRS) [63]. The available bandwidth is reckoned regularly after a certain duration so that the up-to-date bandwidth information is always available. The RR can be successfully made if all the nodes along the route can contribute the bandwidth that suffices the QoS requirements of the session. Akin to PBRS, a Trigger-Based On-Demand Routing (TDR) scheme is proposed in [59]. Beacon is broadcasted regularly in order to collect and update the local resource state information for the neighbouring nodes. During the initial route discovery process, the source node temporarily reserves the bandwidth for a session if its residual resources can sustain the QoS demands. The procedure continues along the route if bandwidth and hop count satisfy the QoS demands. The formal reservation is confirmed when acknowledgement from the destination reaches the source. A drawback of these schemes is that they do not consider to gather the reservation state information from the CS range, which will result in bandwidth over-utilization.

In order to obtain information of bandwidth utilization within the CS range, several schemes are proposed. For example, a Mesh Ad-Hoc Control and QoS Routing with Interference-Aware scheme (MARIA) [43] utilizes enlarged transmission power to broadcast "HELLO" message regularly in order to obtain the information of interfering sessions within the CS range. A drawback of this method is that the enhancement of transmission power will lead to more interference and more power consumption. Another solution to detect the potential interference from the CS range is to relay the state information two-hops away from a node. For instance, in Bandwidth Reservation under Interferences Influence (BRuIT) scheme [61], "HELLO" message is extended to include the information such as the address of sender and the amount of reserved bandwidth. The information embedded in each "HELLO" message will be disseminated twice so that the neighbouring nodes within two-hops can receive it. RR is carried out when the route reply has reached all the

TABLE III
THE FEATURES OF ROUTING SCHEMES WITH RR: A COMPARISON

Scheme	RD	QA	R-RR	CS-IA	AC-C	RM	CA	SR	SC	CL
Tiket-Based [58]	Proactive	Soft QoS	√	×	×	Reactive	×	×	×	×
TDR [59]	Reactive	Soft QoS	√	×	×	Reactive	×	×	√	×
ADQR [60]	Reactive	Soft QoS	×	×	√	Proactive	×	×	×	×
AQOR [44]	Reactive	Soft QoS	×	×	√	Reactive	×	×	√	×
IQOLSR [40]	Proactive	Soft QoS	√	√	√	N/A	×	×	×	×
BRuIT [61]	Reactive/Proactive	Soft QoS	×	√	√	Proactive	×	×	√	×
QRBE [62]	Reactive	Soft QoS	×	√	√	Reactive	×	×	√	√
PBRS [63]	Reactive	Soft QoS	×	×	√	N/A	×	×	√	×
MARIA [43]	Reactive	Soft QoS	×	√	√	N/A	×	×	√	√
DDCMA [64]	Reactive	Soft QoS	×	×	×	N/A	×	×	√	√
ETP [65]	Reactive	Soft QoS	×	×	×	N/A	×	×	√	√

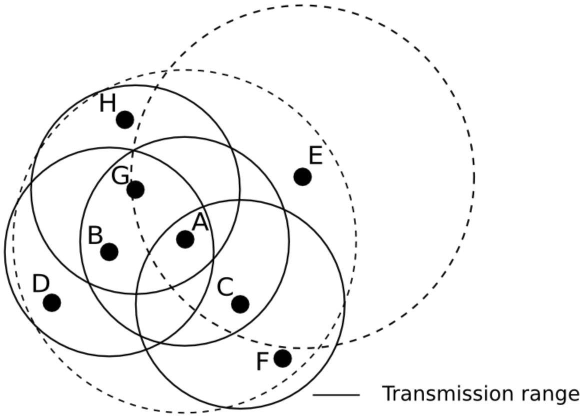

Fig. 7. Provided that node A sends data to its neighbouring nodes within its transmission range, node B, C, G can capture the data and forward the reservation information further by broadcasting an ACK. By doing this, node H, D, F can decode the information and align to the reservation schedule. However, the information can not reach to node E, which resides without any nodes' transmission range. Therefore, node E could still interfere the tranmission of node A.

intermediate nodes before being received by the source. Akin to BRuIT, in [62], a hop relay mechanism is employed. The "HELLO" message is extended to contain the sender's address, its consumed bandwidth as well as the resource state information of its neighbouring nodes. By doing this, a node receiving the "HELLO" message from its one-hop's neighbouring node can obtain the resource state information and aligns to the resource schedule of its neighbouring nodes that locate two-hops away. A shortcoming of these mechanisms is that the information collection of available resources closely depends on the geographical position of the interfering nodes. As shown in Fig. 7, if an interfering node locates out of the transmission range of all the one-hop neighbouring nodes of the host, the information collection can not be achieved.

A QoS routing and signalling mechanism named Ad-Hoc QoS On-Demand Routing (AQOR) is proposed in [44]. Upon the receipt of feedback containing routing metrics such as minimum round trip delay, source node selects the route with lowest end-to-end delay and sends out data packet. Meanwhile, temporary RR is made at each node across the selected route. The reserved bandwidth is only available for a certain period of time for the session. The resources will be automatically released if no data makes use of them for a given duration. A shortcoming of this scheme is that inaccurate resource releasing will happen if collisions occur during the data transmissions.

Considering the cross-layer interaction, a scheme called DDCMA is proposed [64]. Once route resources have been reserved by a session, DDCMA can let nodes to transmit ACK and RTS simultaneously in order to reduce delay. It can also defer the re-routing process for RTSNs by re-sending packets to the destination once retransmission limit is reached. However, DDCMA does not achieve effective cooperation or coordination between MAC and routing layer. In [65], a MAC-aware routing scheme is proposed. A new routing metric called Expected Throughput (ETP) is modelled, taking into account the channel contention in the MAC layer. It can assist reactive routing scheme to measure the available capacity more accurately. A problem of this scheme is that the interference from the CS range is not considered in ETP.

Common Advantages and disadvantages: The advantage of reactive schemes is that it can consider the interference from the CS range via route discovery and confirmation processes. It can also avert the wastage of channel capacity caused by proactive routing overhead. However, reactive schemes incur additional delay for a session since the route discovery is always needed to be implemented before the data transmission. In terms of scalability, reactive schemes scale better than proactive schemes due to the restricted overhead. However, the huge amount of flooding packets for searching routes is still a big issue in a large-scale network. Tab. III shows the comparison of the routing schemes with RR. Note that in Tab. III, RD, QA, R-RR, CA-IA, AC-C, RM, CA, SR, SC, CL stand for Route discovery, QoS Assurances, Redundant RR, CS Interference-Aware, AC Coupling, Route Maintenance, Collision Avoidance, Spatial Reuse, Scalability and Cross-Layer design, respectively.

Routing scheme can be effective in selecting a route with sufficient resources for a RTSN in order to implement RR. However, routing scheme can not make actual resource scheduling. Resources reserved for a session may be interrupted because routing scheme can not control over the transmission attempts of interfering sessions. The information of resource usage such as channel busyness ratio [31], [35] can be obtained from MAC layer and can help routing scheme to implement RR decision more accurately. However, it still can not solve the collision issue.

B. MAC Scheduling Mechanisms with RR

MAC scheduling mechanisms can implement bandwidth allocation and service differentiation for data sessions. To guarantee the QoS for RTSNs, dedicated resources should be allocated to them through an efficient MAC RR scheme. To this end, different solutions have been proposed following both centralised and distributed manners. Some key schemes are summarized in this sub-section and their comprehensive comparison is given in Tab. IV. Note that in Tab. IV, TP, MAC-S, FN, DRM, CA, SR, SC, CL stands for Topology, MAC Standard, Fairness, Dynamic Resource Management, Collision Avoidance, Spatial Reuse, Scalability and Cross-Layer design, respectively. C and D in column two represent centralised and distributed.

1) ***Centralised QoS MAC schemes****:* To date, many research works have been concentrated on how to enhance QoS or to provide guaranteed QoS following centralised schemes in IEEE 802.11-based wireless networks. Existing solutions can be generally classified into several sub-classes: TDMA-based, dynamic TXOP tuning, multipolling and polling sequence tuning schemes.

a) ***TDMA-based schemes****:* The centralised MAC schemes using IEEE 802.11-based technique can follow the TDMA-based mechanism because of the infrastructure-based topology. For example, a Software TDMA (STDMA) scheme is proposed in [67]. It splits the channel airtime into scheduled cycles. By gathering the traffic load information from either data packet which piggybacks additional information or the traffic request frame, the AP can schedule the transmission for different nodes using an algorithm that is similar with weighted fair queuing [68] and release the allocated resources when it is notified that there is no data packet buffered in the queue of a corresponding node. Another TDMA-based scheme called Isochronous Coordination Function (ICF) is proposed in [69]. After receiving the RR request from all the nodes, a polling frame including a status sector is broadcasted by the AP. Constructed by a set of polling bit, the status sector will assign differentiated polling bits to the nodes in order to schedule their transmissions. These terminated nodes can re-claim resources by sending a reconnection frame to the AP. A drawback of these schemes is their implementation complexity.

An effective polling mechanism named Deterministic Back-Off (DEB) is proposed in [70]. It enables CF-Poll frame to carry information of distinct back-off counters to the nodes in order to differentiate their transmission slots in the CFP. A shortcoming of this scheme is that the back-off counter assignment does not consider prioritization and the fairness.

Common advantages and disadvantages: TDMA-based schemes can directly achieve guaranteed RR for each RTSN owning dedicated time-slots. In addition, polling overhead can be reduced by using scheduling control message in front of each TDMA cycle. However, the contention-free transmission is still not guaranteed because it is vulnerable to the carrier sense errors. Although assigning large value of guard interval can help to alleviate this issue, the efficiency of bandwidth utilization will be degraded. In addition, the requirement of tight synchronization is difficult to be implemented. Finally, the inflexibility issue of TDMA-based schemes prevents them from adapting to dynamic bandwidth demands [97].

b) ***Dynamic TXOP tuning schemes****:* The advent of VBR session facilitates the flexibility and accuracy of encoding sound and video data [98]. However, the legacy IEEE 802.11 polling mechanisms can not support VBR session because they can only implement static RR [53]. Existing schemes mainly focus on tuning the size of allotted TXOP dynamically for each VBR session. For instance, In [75], an AP Dynamic Access (AP-DA) mechanism, together with an Access Time Based Admission Control (ATAC), is proposed. Using token bucket mechanism to distribute maximum transmission time for each nodes, TXOP can be allocated to each node with specific QoS demands and tuned in each SI. However, the tuned resources for each interval may not accurately match the varying demand for VBR. This can cause bandwidth wastage. In [71], an optimization-based HCCA (PRO-HCCA) is proposed to solve the fairness issue of VBR sessions with distinct delay bounds. An accounting mechanism is applied for scheduling the resources for each session according to its service deadline. A problem of this scheme is that it is too complicated to be implemented.

To support VBR sessions in HCCA, a solution is proposed in [99]. It can balance the trade-off between the delay caused by queue size and the efficiency of bandwidth allocation. In line with the specific traffic load, bandwidth is allocated dynamically. In [22], two feedback-based scheduling mechanisms, namely, Feedback Based Dynamic Scheduler (FBDS) and Proportional-Integral (PI)-FBDS, are proposed for providing delay guaranteeing for both Constant Bit Rate (CBR) and VBR sessions. A closed-loop control scheme is utilized for limiting the queuing delay under a bounded value which reflects the QoS requirement. For meeting the delay bound, TXOP allocation will be dynamically changing according to the feedback retrieved from the queue size. Another example is Adaptive RR over WLANs (ARROW) [74]. According to the information of queue size informed by a node, the AP will dynamically assign TXOP with sufficient duration which can serve the transmission of pending packets. A drawback of these schemes is that dynamically tuning the size of TXOP will cause difficulties for other high-priority sessions to obtain accurate information of available bandwidth.

Focusing on the enhancement of bandwidth efficiency in HCCA, an Equal-Spacing-Based scheme (ESB) is proposed in [73]. Using an equal-spacing rate monotonic algorithm, the scheduling period and TXOP size for each RTSN can be computed according to its delay bound. The equal-spacing scheduling for the periodical resources allocated to a RTSN can further guarantee its strict delay requirement. One of its drawback is that the allocation of TXOP does not consider the fluctuation of traffic parameters such as packet size. This may

TABLE IV
THE FEATURES OF MAC SCHEMES WITH RR: A COMPARISON

Scheme	TP	QoS assurances	MAC-S	CS	AC	Applications	FN	DRM	CA	SR	SC	CL
STDMA [67]	C	Guaranteed QoS	DCF	×	×	Single-hop	√	×	√	×	×	×
ICF [69]	C	Guaranteed QoS	PCF/HCCA	×	×	Single-hop	√	√	×	×	×	×
DEB [70]	C	Enhanced QoS	HCCA	×	×	Single-hop	×	×	√	×	×	×
PRO-HCCA [71]	C	Guaranteed QoS	HCCA	×	×	Single-hop	×	√	×	×	×	×
FBDS [22]	C	Guaranteed delay	HCCA	×	√	Single-hop	×	×	×	×	×	×
EFMM [72]	C	Guaranteed delay	PCF/HCF	×	√	Single-hop	√	√	√	×	×	×
Q-PCF [21]	C	Guaranteed QoS	PCF	×	√	Single-hop	√	√	√	×	×	×
ESB [73]	C	Guaranteed QoS	HCCA	×	√	Single-hop	√	√	×	×	×	×
ARROW [74]	C	Enhanced QoS	HCCA	×	×	Single-hop	√	√	×	×	×	×
ATAC+AP-DA [75]	C	Enhanced QoS	PCF	×	√	Single-hop	√	√	√	√	×	×
CSSR [76]	C	Enhanced QoS	PCF	×	×	Single-hop	√	×	×	×	×	×
APMS [77]	C	Enhanced QoS	PCF	×	×	Single-hop	√	√	×	×	×	×
MRP-OFDMA [78]	C	Enhanced QoS	HCCA	×	×	Single-hop	×	×	×	×	×	×
RTS/CTS	D	Soft QoS	802.11	×	×	Single-hop	×	×	√	×	×	×
AROMA [38]	D	Soft QoS	DCF	×	√	Single-hop	√	×	√	×	×	×
CR-MAC [79]	D	Soft QoS	DCF	×	×	Single-hop	√	√	√	×	×	×
EBA [80]	D	Soft QoS	DCF	×	×	Single-hop	×	√	√	×	×	×
ReB [81]	D	Soft QoS	CSMA	×	×	Single-hop	×	√	√	×	×	×
CRF [82]	D	Soft QoS	DCF	×	×	Single-hop	×	×	×	×	×	×
DBASE [83]	D	Soft QoS	DCF	×	×	Single-hop	√	√	√	×	×	×
ReAP [84]	D	Soft QoS	EDCA	×	×	Multi-hop	√	×	√	×	√	√
APHD [85]	D	Soft QoS	EDCA	×	×	Multi-hop	√	×	√	×	√	√
DPCF [86]	D	Soft QoS	DCF	×	×	Single-hop	×	×	√	×	×	×
CPM [87]	D	Enhanced QoS	DCF	×	×	Single-hop	√	×	√	×	√	×
DBRS [88]	D	Soft QoS	DCF	×	×	Single-hop	√	×	√	×	×	×
BCR-CS [89]	D	Soft QoS	DCF	×	×	Single-hop	×	×	√	×	×	×
PMRT [90]	D	Soft QoS	DCF/EDCA	×	√	Single-hop	×	√	×	×	×	×
R-CSMA/CA [91]	D	Soft QoS	DCF	×	×	Multi-hop	×	√	√	√	×	×
DRRP [92]	D	Soft QoS	EDCA	×	×	Single/Multi-hop	×	√	√	×	√	×
BWSS [93]	D	Enhanced QoS	EDCA	×	√	Single-hop	√	√	√	×	×	×
DARE [94]	D	Enhanced QoS	DCF	×	×	Multi-hop	×	√	√	×	×	×
MCDR [95]	D	Enhanced QoS	DCF	×	×	Single-hop	×	×	×	×	×	×
EDCA/RR [96]	D	Enhanced QoS	EDCA	×	√	Single/Multi-hop	√	√	√	×	√	√

incur high packet loss ratio for VBR sessions.

Common advantages and disadvantages: To accommodate the VBR sessions, dynamic RR can effectively enhance the usage of channel capacity. On the basis of analytical model, tuning TXOP for a VBR session can improve its delay performance and alleviate the packet loss ratio. However, tuning TXOP dynamically will result in oscillation of the available resources in the CFP, posing difficulties for other kinds of sessions to reserve bandwidth. If the VBR session keeps at a high data rate for certain period, the unfairness occurs when other sessions wish to obtain resources in the CFP.

c) ***Multi-polling schemes:*** In conventional polling-based mechanisms, control overhead degrades the QoS performance because each node has to be polled by the AP before grabbing the channel. To deal with this issue, many contributions strive to alleviate polling overhead while managing the resources efficiently for data transmission. For example, a Multi-Polling mechanism with OFDMA scheme (MRP-OFDMA) is proposed in [78]. The AP can use a single multi-polling request frame to poll multiple nodes. These nodes can receive the information of their own scheduled transmission periods via the polling message. Another multi-polling mechanism (this mechanism is referred to as EFMM) is proposed in [72]. The multi-polling frame assigns differentiated back-off parameters to the nodes in the polling list. Upon the receipt of multi-polling frame, each node will enter a back-off process and transmit data when its back-off time-outs. A problem of these schemes is that they can not adapt to the condition in which the RTSNs have dynamic QoS demands.

The work in [100] proposes a multi-polling mechanism with the consideration of different SIs for QoS nodes. Note that the QoS node indicates the node that is compatible with IEEE 802.11e standard and has the ability to request specific transmission parameters. Each HC can recursively add new QoS nodes into the multi-polling list and poll them together with other QoS nodes in the list if the extended multi-polling frame does not offend the delay bound of other QoS nodes. A problem of this scheme is that enlarged multi-polling frame caused by the increasing number of QoS nodes will cost additional network bandwidth.

Common advantages and disadvantages: Multi-polling mechanisms can achieve higher bandwidth efficiency compared with single-polling schemes. However, the common issue in multi-polling solutions is that all the polling information is assigned to one or a few control frames and this will lead to the wastage of the allocated bandwidth or the unfairness if the frames with polling information can not be received properly by certain nodes due to the problems such as error-prone channel condition. Although multiple transmissions of the control frame can alleviate the issue, this will consume additional network bandwidth [69].

*d) **Polling sequence tuning schemes:*** Since multiple nodes are involved under the control of the AP, how to prioritize the sessions with stringent QoS demands in the CFP is another issue. In legacy IEEE 802.11, each node has static position in the polling list and the AP polls each node using round-robin algorithm whereby nodes are polled in ascending sequence according to their Association IDs (AIDs). This method can be further improved in order to pledge the fairness or achieve service differentiation based on specific QoS metrics.

In [69], a PCF-based centralised scheme called Cyclic Shift and Station Removal polling scheme (CSSR) is proposed. CSSR periodically shifts the order of the nodes within the polling list during each cycle. By doing this, discarded packets can be evenly distributed to all the nodes rather than a few number of nodes. This can enhance the number of nodes that the PCF can handle. However, specific QoS requirements of each session are not considered in the shift procedure.

In [77], an Adaptive Polling MAC Scheme (APMS) utilizes the detection of silence-to-talkpurt state to dynamically manage the active node list in which nodes can have dedicated resources in the next reservation-period. Another example is QoS PCF (Q-PCF) [21]. Q-PCF splits each CFP into three sub-durations: prioritization period, collision resolution period and polling period. To differentiate the priority of each node, signalling messages will be exchanged between the AP and the nodes during the prioritization period. Nodes with higher priority sessions can get access to the polling list earlier than others with lower priority sessions. A problem of these scheme is the implementation complexity.

Common advantages and disadvantages: Polling sequence tuning schemes can enhance the fairness among the nodes or provide prioritized services to sessions based on their QoS demands. The shortcoming is that they does not essentially solve the problem of limited bandwidth efficiency in traditional polling mechanism. For instance, polling overhead for each session is not radically eliminated in most of the polling sequence tuning schemes.

Although centralised RR schemes can easily achieve synchronization with the support of central controllers, they can not be employed in distributed environment. On the other hand, issues such as the complexity and back-haul access also prevent centralised RR schemes from being applied extensively. In addition, the complexity of centralised schemes result in poor scalability as the frequent exchange of control messages can hardly adapt to the dynamic change of network size. In order to solve these problems, distributed RR schemes are needed.

*2) **Distributed QoS MAC schemes:*** Distributed topology becomes a necessity, for example, in wireless mesh networks and wireless sensor networks. Distributed networks can implement both single-hop and multi-hop communications and do not need any support of centralised devices. Thus, in a distributed network, peer-to-peer communications can be directly achieved without back-haul access to APs or base stations. Compared with centralised schemes, distributed schemes often utilize signalling or piggyback mechanism to disseminate resource information. The evenly distributed control message propagation will make them scale better than centralised schemes in which the major task of RR is always assigned to the centralised devices.

This sub-section discusses distributed RR schemes proposed in IEEE 802.11 based wireless networks. In general, existing distributed RR schemes can be classified into several types according to the way the reservation is made. If the reservation is made within contention-based environment, it is referred to as contention-based RR scheme. If the bandwidth is reserved in the CFP that is separated from the CAP, it is named as hybrid MAC RR scheme.

*a) **Contention-based schemes:*** As for contention-based RR schemes, the reservation is made via disseminating control messages such as RTS/CTS or piggybacking the resource state information in data packet in order to inform the neighbouring nodes.

Since the RTS/CTS handshaking mechanism can be regarded as a kind of contention-based RR scheme, several contributions aim at modifying RTS/CTS handshaking [101]. For instance, an Asynchronous Reservation Oriented Multiple Access (AROMA) is proposed in [38]. It couples with AC that is implemented by Reservation-RTS (R-RTS) and CTS handshaking and reserves bandwidth for RTSNs when available bandwidth is sufficient. Another example is Channel Reservation MAC (CR-MAC) scheme [79]. It utilizes R-RTS to reserve bandwidth for a node within the reservation period. A reservation waiting list is created for recording the sequence of reserved bandwidth of nodes within the transmission range. A common issue of these schemes is that they mainly focus on the design of AC but fail in solving the channel contention and interference issues.

On the other hand, some solutions aim to alleviate the overhead caused by ACK, deferral and back-off in order to reserve more bandwidth for data transmission. For example, a concatenation mechanism is proposed in [87]. It can link multiple frames in the queue and then transmit them consecutively if the size of the concatenated frame does not exceed a concatenation threshold. A Channel Reservation Function (CRF), proposed in [82], mainly uses negotiation procedure to sort the packets heading to the same destination and these packets can be transmitted consecutively. A problem of these schemes is the trade-off between the fairness and the consecutive data transmission. Reserving excessive bandwidth for multiple data frames of one session will cause degraded performance of other sessions.

Several schemes are considered to reserve back-off slots for data transmission. For instance, an Early Back-off Announcement (EBA) [80] improves DCF by asking a node to advertise its next back-off value. The RR is achieved if other neighbouring nodes does not occupy the resources. A drawback of this scheme is that negotiation of resource state information will cause wastage of bandwidth. In [81], a Reservation-Based Back-Off mechanism (ReB) is proposed.

ReB employs a fixed back-off cycle which includes certain number of slots for the nodes in a contending region to reserve. In [88], a Distributed Back-Off Reservation and Scheduling scheme (DBRS) mainly utilizes a distributed slot table for each node to dynamically record the amount of contending nodes of themselves. It utilizes a slot window timer to synchronize the RR for the nodes within the transmission range. Another example is Back-Off Counter Reservation and Classifying Stations (BCR-CS) [89]. A back-off counter table is used for synchronizing the contention parameter of the nodes in a contending region. The next back-off counter of a node is chosen from a slot information set that contains all the available or unreserved slots. A drawback of these schemes is that the information of available slots can not be notified by the interfering nodes within the CS range.

Many contention-based MAC schemes follow cross-layer design. For example, in [84], a dynamic ReAllocative Priority (ReAP) scheme is proposed. Using the hop information retrieved from routing layer, the available bandwidth for a certain priority queue tends to be reserved for the packets that have to traverse more hops. Another example is called Adaptive Per Hop Differentiation (APHD) [85], it also utilizes the hop information from the routing layer in order to reserve bandwidth for the packets with lastest deadline per hop. Despite of the effective cross-layer interaction, the RR for these apporaches relies on the random channel access for certain priority queue without any reservation protection achieved by signalling. Thus, the reserved transmissions are vulnerable to interference and channel contention.

Common advantages and disadvantages: Contention-based RR schemes usually enjoy less reservation control overhead compared with hybrid MAC RR schemes. Some state information can be piggybacked in control frame (i.e. RTS and CTS) or data frame so that additional signalling is not needed. In addition, since the RR is implemented within the contention-based environment, contention-based RR schemes can achieve higher multiplexing gain and support better resource sharing. The simplified design of contention-based RR schemes can facilitate their scalability. However, the negative aspect is that deferral and back-off as overheads can not be completely eliminated. In addition, state information of reservation can not be notified by the interfering nodes that reside within the CS range but outside the transmission range. Thus, these issues prevent contention-based RR schemes from guaranteeing the QoS for RTSNs.

b) ***Hybrid-based schemes:*** Different from contention-based RR schemes, hybrid MAC RR schemes split the channel airtime into super-frames that contain CFP and CAP. The CFP can be reserved by RTSNs with strict QoS demands. On the other hand, the CAP is maintained to provide sustainable services for NRTSNs and they follow contention-based channel access. Due to the nature of contention in wireless medium, hybrid MAC RR schemes rely on additional coordination among competing nodes [23]. Fig. 8 shows the difference between contention-based MAC RR and hybrid MAC RR.

Several schemes implement hybrid MAC RR in single-hop communication. For instance, a scheme called Periodic Medium Reservation Timer (PMRT) is proposed in [90]. A reservation interval is used for each RTSN to decide the distance between its dedicated time-slots so that real-time packets can be transmitted periodically. In Distributed Point Coordination Function (DPCF) [86], the CFP is operated following PCF mode. The destination as the master node will poll its neighbouring nodes using certain scheduling schemes, for example, round robin polling. DPCF inherits several drawbacks from PCF. For example, service differentiation for distinct types of sessions is not considered. In [83], a Distributed Bandwidth Allocation/Sharing/Extension (DBASE) scheme is proposed. A sequence ID register and an active counter are maintained in each node for recording the reservation access sequence in the CFP and the total amount of active nodes with reservation. In [93], several Bandwidth Sharing Schemes (BWSS) are proposed for guaranteeing the QoS for RTSNs in IEEE 802.11e contention-based distributed Wireless LANs. Channel airtime is split into sharing region for RTSNs and guard period for the fairness toward NRTSNs. Using various forward and backward sharing schemes, dedicated bandwidth can be reserved for certain RTSNs and the rest of the sharing region are distributed to other RTSNs. Another example is Multi-Cell Dynamic Reservation (MCDR) [95]. It further splits CFP into two parts and allocates them to video sessions and voice sessions respectively. Meanwhile, the residual bandwidth in the CFP is allotted to other types of sessions. A common issue of these schemes is that they do not consider the trade-off between the QoS guaranteeing and the reservation capacity.

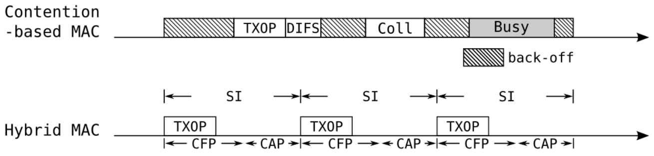

Fig. 8. Contention-based MAC RR and hybrid MAC RR

Some works are considered to implement hybrid MAC RR in multi-hop communication. For instance, Reservation CSMA/CA (R-CSMA/CA) [91] devises a reservation coordination function by which RTSNs can make dedicated slots reservation through implementing a three-way signalling process. A disadvantage of R-CSMA/CA is that the slots reservation does not consider the QoS requirements of each RTSN.

In [92], a RR scheme called Distributed Reservation Request Protocol (DRRP) is proposed. Neighbouring nodes can overhear the data frame which contains the reservation request from the senders. They can decode the resource state information in order to align to the new reservation schedule during the reserved period. A Distributed End-To-End Allocation of Time Slots for Real-Time Traffic (DARE) scheme is proposed in [94]. It disseminates the state information of reservation such as periodicity and reserved time-slots during the reservation set-up period. Each node can get dedicated time-slots to transmit data if the RR is confirmed. A problem of these schemes is that the bandwidth is reserved without the consideration of spatial reuse enhancement.

A cross-layer example is EDCA with Resource Reservation (EDCA/RR) [96]. EDCA/RR consists of an ACA and a MAC scheduling mechanism. In the case of the single-hop communication, synchronization is implemented by broadcasting signalling message. For multi-hop communication, route discovery process is extended for requesting RR along the route. A shortcoming of this scheme is that RTS/CTS handshaking is still employed in each reserved TXOP, which will incur unnecessary overhead.

Common advantages and disadvantages: Hybrid MAC RR schemes can provide QoS enhancement for RTSNs via reserving dedicated bandwidth. Meanwhile, the CAP can pledge the fairness toward NRTSNs. However, the explicit signalling as an additional overhead will have negative impact on bandwidth efficiency and also result in degraded performance for RTSNs. On the other hand, none of the schemes consider solutions to the interference from the CS range among the reservation period. This causes interruptions for the transmissions among the reservation period and thus violates the QoS assurance. Further, low efficiency of spatial reuse is another open issue that will result in low bandwidth efficiency for hybrid MAC RR schemes.

VIII. TRENDS AND PROGRESS IN THIS FIELD

In the previous section, the existing RR schemes are discussed. Having summarized the common advantages and disadvantages for each category, in this section, the trend and progress for both routing and MAC schemes with RR are pointed out.

A. QoS Routing Schemes with RR

The trend and development of routing RR scheme can be identified from several aspects such as reliant MAC scheme, efficiency of RR, interference detection and system model.

1) Reliant MAC scheme: Since reservation-based MAC scheme such as TDMA can provide a simple way for quantifying channel capacity, earlier QoS routing RR schemes were proposed based on contention-free MAC schemes [8]. However, since the tight synchronization is difficult to be implemented, later research began concentrating on contention-based MAC schemes. Many research works have been focused on routing schemes with RR in IEEE 802.11-based wireless networks, as described in Section VII-A.

2) Efficiency of RR: The earlier routing schemes with RR had the consideration of alleviating the reservation control overhead. They also implemented multiple routes for RR in order to provide a secondary route for reserved transmission if the primary route is not available. But they ignored the efficiency of bandwidth utilization and the fairness to other sessions. Some newer schemes attempted to solve the problem caused by the redundant reservation and tried to enhance the bandwidth efficiency. For example, the soft/hard reservation switching mechanism can dynamically reuse the pre-reserved resource when it becomes idle. Some solutions considered to utilize additional signalling for RR to reserve bandwidth along the route rather than integrating reservation negotiation within the route discovery process so that RR will be made along a specific route without any additional wastage.

3) Interference detection: As for interference detection, earlier schemes did not concern about any interference from the neighbouring routes or nodes. Although available bandwidth was chosen as a routing metric, it was not thoroughly investigated in detail. In addition, some of the previous schemes also ignored the violation of QoS for existing sessions due to newly arrived RTSNs. Latter solutions strived to study how to estimate the available bandwidth more precisely. They also tried to employ AC which can admit new sessions according to the estimated available bandwidth. However, some of the bandwidth estimation processes were implemented without the consideration of interference within the CS range. This can result in inaccuracy of bandwidth estimation and thus lead to over-utilization of bandwidth. To deal with this problem, several interference-aware solutions [36], [43] have been proposed by some latest QoS routing schemes. Together with the support of AC, the interference-aware routing schemes can achieve higher QoS improvement. Thus, future routing schemes with RR have to consider both AC and interference within the CS range in order to provide better QoS.

4) System model: The system models produced from the earlier works were relatively simple and imprecise. Since the interference within the CS range needs to be taken into account. Some recent models include graph theory as well as maximum clique in order to consider the interference within the CS range while estimating the available bandwidth, for example [40], [43].

As mentioned in Section IV-A, QoS routing can merely find out the route with sufficient resource for a RTSN. It can not implement actual resource scheduling. Thus, QoS routing can hardly provide guaranteed QoS for RTSNs under dynamic traffic conditions.

B. Centralised QoS MAC Schemes with RR

Since the MAC scheme has the functionalities of bandwidth allocation and service differentiation for distinct types of sessions, it can provide higher priority of services to RTSNs through reserving bandwidth to them in IEEE 802.11-based wireless networks. The trends in the development of MAC layer RR schemes can be found in terms of both centralised and distributed schemes. The progress of centralised schemes can be identified from reliant MAC standard and dynamic RR perspective.

1) Reliant MAC standard: Since the RR was inherently implemented in PCF, earlier centralised schemes mainly focused on providing improvement based on PCF, for instance, by alleviating control overhead, adjusting the size of reserved bandwidth for each RTSN, scheduling the bandwidth allocation for fairness. With the advent of HCCA which was developed from PCF, newer schemes concentrated on improving HCCA in order to provide better QoS toward different applications such as CBR and VBR sessions.

2) Dynamic RR: Instead of reserving bandwidth statically in earlier works, some latest solutions based on HCCA focused on guaranteeing the QoS for each RTSN via dynamic RR. Several of them devised system model to validate the system performance or provided accurate parameters to achieve efficient RR in order to increase the number of RTSNs that can obtain guaranteed QoS. Another tendency of the centralised RR schemes design is to improve the QoS performance for VBR applications/sessions while considering the enhancement of network capacity. Recent schemes strived to deal with the issues of static RR by dynamically varying the size of allocated bandwidth according to the varying traffic condition of VBR sessions and their QoS demands.

C. Distributed QoS MAC Schemes with RR

Apart from centralised RR schemes, implementing distributed MAC RR schemes is also effective in providing guaranteed QoS for RTSNs. The progress can be identified from single/multi-hop communication, interference detection and QoS demand perspective.

1) Single/multi-hop communication: Earlier contributions mainly implemented RR for single-hop communications because it was relatively easy to achieve synchronization within the transmission range. Reservation state information can be simply carried by data frames or propagated by signalling messages. Since multi-hop communication in distributed wireless network becomes indispensable, newer schemes attempted to implement distributed RR in order to provide guaranteed QoS for RTSNs in multi-hop communication.

2) Interference detection: In terms of multi-hop RR, the majority of the works relied on explicit signalling. However, most of the existing works only considered to reserve bandwidth within transmission range of a QoS route rather than CS range. This may cause severe collision during the transmissions in the reservation period as the interfering nodes reside within the CS range can not obtain the resource state information of reservation. This problem needs to be addressed in the future.

3) RR against QoS demand: Another tendency for the design of distributed MAC RR schemes is to optimize reserved bandwidth based on the QoS requirements of each RTSN (i.e. delay and throughput). This was originally considered in the HCCA-based schemes in which each RTSN can reserve TXOP with different size in order to satisfy its distinct demands. As a mean to provide guaranteed QoS for RTSN, this factor is expected to be considered in both centralised and distributed schemes. In distributed schemes, the majority of contention-based RR schemes did not consider to guarantee specific QoS requirements of RTSNs. As for hybrid MAC RR schemes, the TXOP for a RTSN can be adjusted in order to meet certain requirements such as throughput. However, meeting delay bound is still a challenging issue. The optimized RR against QoS demand can give a solution to the trade-off between the network capacity and the level of QoS provisioning.

IX. CONCLUSION

As an important way to provide QoS, schemes based on resource reservation have been concentrated on for many years. In this paper, we firstly outlines the concept of RR and its background, following by the general review of the IEEE 802.11 MAC standard among which the advantages and disadvantages of each standardised channel access method are investigated. We also specify the challenges and key elements of designing a RR scheme. In the subsequent section, the consideration of devising a RR scheme is discussed and the design trade-offs is involved after. The classification is done based on different types of schemes as well as their functionalities. Nearly 44 schemes are summarized. For each kind of scheme, advantages and shortages are clearly highlighted.

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