Chapter 5
Case Study: Media Access in CRN Framework

Based on the survey done in Sect. 1.7 and Chap. 2, the media access control protocols are classified into two broad categories: *random* and *time-slotted* media access schemes, each having its pros and cons. Recently a new class of access scheme, known as *hybrid* schemes has been developed with better performance than that of the random and time-slotted access schemes. Most of these scheme are network-model dependent, and therefore a change in their operation from ad-hoc to infrastructure or vice-versa is impractical. In a multi-channel environment, support for broadcast and multicast is tedious in nature and requires implementation of flooding operation.

In this section, a media access scheme is discussed which is hybrid in nature and provides unique features of multicast and broadcast without network flooding [1]. The discussed media access scheme allows contention of nodes to be distributed across channels, therefore mitigating the problems of channel saturation. The scheme also allows nodes to prioritize packets for the purpose of QoS provisioning while facilitating power saving mode for energy conservation.

As discussed in Sect. 3.2, the units responsible for the design of QoS provisioning media access scheme are highlighted in Fig. 5.1. The mac protocol unit (MPU) receives the list of channels from channel selection and management unit (CSMU). It also receives the information about the QoS requirement on long run statistical behavior from the QoS control unit. Based on the information received the MPU generates a MAC instance. The MAC instance on the basis of QoS requirement of individual packet (access category) defines the individual packet behavior.

5.1 System Model

The system comprises of N cognitive radio user operating in an ad-hoc environment comprising of C channels. A channel from one of the ISM bands or a channel with high availability is selected as a rendezvous channel (RC). RC is utilized for the

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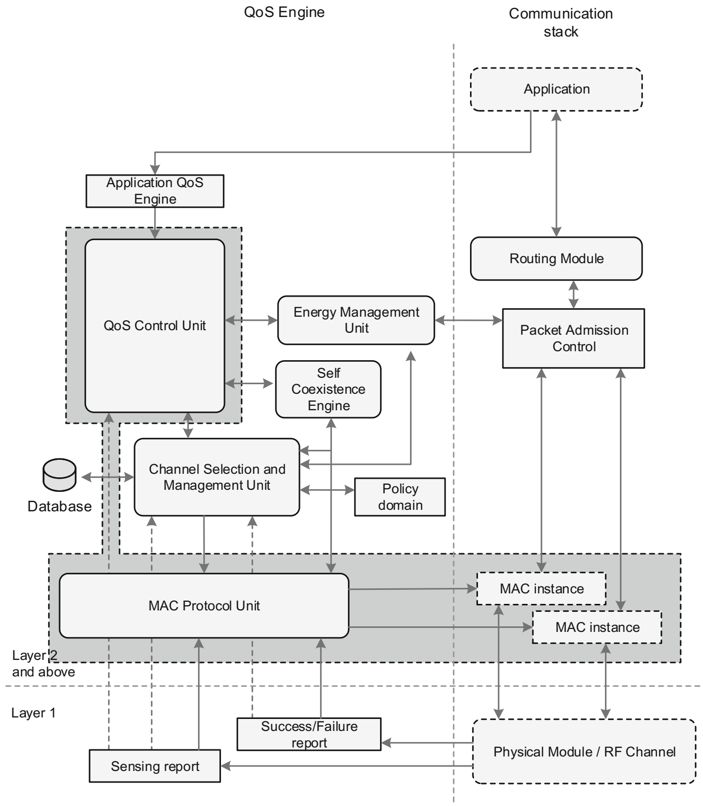


Fig. 5.1 Units in the CRN framework responsible for QoS provisioning media access scheme

purpose of network information interchange. The hardware complexity of CR users is equivalent to that of the half-duplex transceiver with sensing capability.

5.1.1 Traffic Type

In modern world, conventional wireless network has to support multitude of different data types due to increase in different types of applications. In a broad sense, data traffic can be classified into four categories as discussed in Sect. 3.1.1 and shown in Table 3.1. Some applications based on voice or video services require delay bounded access, which require special handling of such packets.

As discussed in Sect. 3.1.1, the resource access delay suffered by a packet in the network is governed by the access scheme utilized by the scheme. An access scheme utilizes packet admission control through the introduction of different arbitration spaces for different packets. Discussion on arbitration space is provided in Sect. 5.2.1.

Apart from arbitration space, QoS is governed by the reservation of bandwidth for a particular traffic. This ensures that the traffic is provided with enough bandwidth to support the level of QoS desired.

5.1.2 Channel Classification

The discussed scheme utilizes multiple channel for its operation, where different channels serves different purposes. The channels utilized in the system are classified into two types: *Data* and *Rendezvous* channels. Users in the network perform exchange of data packets over data channels while the exchange of control information is done over rendezvous channel (RC). The discussed media access scheme supports two types of data transfer: *contention* based and *reservation* based data transfer. The support for dual data transfer types requires usage of two different access etiquettes. Therefore data channels are further classified into *Contention based channels* and *Reservation based channels*. Contention based channels (CBC) follow the etiquette of contention based data transfer. Nodes which are on CBC perform contention whenever a data transfer is required. Reservation based channels (RBC) follow the etiquette of data transfer based on reservation. For the purpose of reservation, nodes perform contention ahead of real data transfer on RBC. Therefore this type of channel has two separate data period: contention (denoted by ad-hoc transmission indication message (ATIM) period) and reserved data period. A reserved data period is further sub-divided into data slots; each of which represents a data packet transfer. During contention, nodes contend to reserve data slots, and during reserved data period, scheduled nodes perform communication. Reservation based channels allow implementation of higher priority stream based data services (for example voice and video).

The system comprises of non-hopping nodes where nodes reside on a channel as long as channel ceases to be free or nodes want to switch to another channel for some reason. From a node's perspective, channels are classified as *Home channel* and *Foreign channel*. Home channel is a channel in which a node chooses to reside while all other channels from this node's perspective are termed as foreign channels. A node belonging to home channel is termed as *Home node* and all other nodes are termed as *Foreign nodes*.

5.1.3 Quiet Period Distribution

As discussed in Sect. 3.4.2, quiet period on a channel is a time duration during which all CR users on that channel stop their communication so that effective spectrum sensing can be performed. Quiet periods are designed to be periodic in nature, so that nodes can detect an incumbent activity during the start of the current/next frame. Sensing can be classified into two types: *in-band* and *out-of-band* sensing. In-band sensing refers to sensing of home channel by home nodes while out-of-band sensing refers to sensing done by nodes on foreign channels. To improve the overall throughput of the system, the quiet periods on all channels are distributed such that they do not overlap. This allows in-band and out-of-band sensing to be performed without any throughput loss.

5.2 Hybrid Media Access Scheme

The design of the discussed MAC scheme with two reservation based channels, two contention based channels and a rendezvous channel is shown in Fig. 5.2. Each channel in the system is divided into fixed length time frames known as superframes. The superframe of all data channels are overlapped and synchronized with each other. Rendezvous channel is synchronized with data channels with a forward offset value of size of rendezvous channel beacon (RCB). Therefore, the start of superframe of data channels are overlapped and synchronized with the end of the RCB of rendezvous channel.

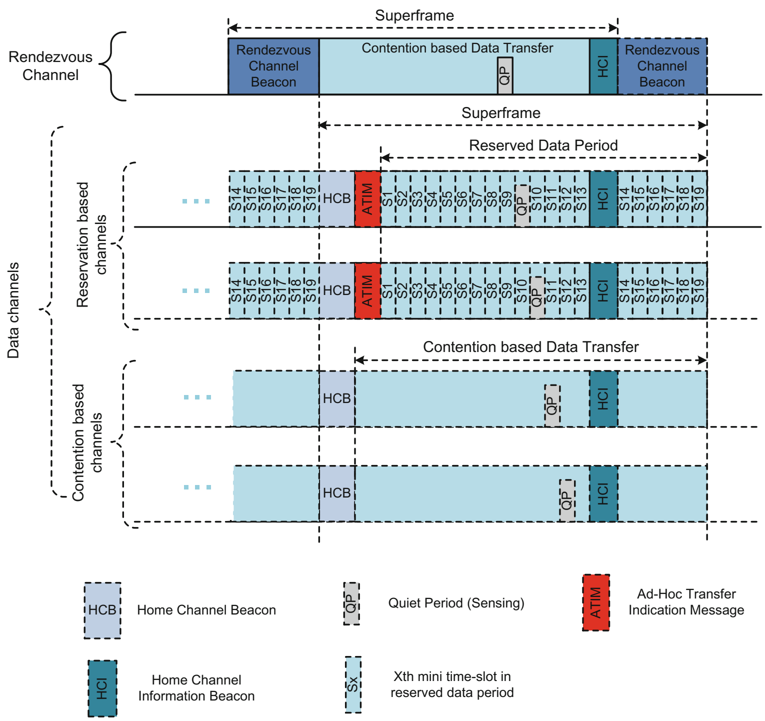


Fig. 5.2 MAC frame structure

The superframe of all channels is composed of different intervals designated for specific purposes. Common intervals among all superframes are quiet periods (QP) and home channel information beacon (HCI). During QP, all nodes on that channel stop their transmission and perform *in-band* sensing. During this period, any foreign node (i.e. node on some different channel than that of the current QP) can perform *out-of-band* sensing on this channel. During HCI, all nodes in their respective home channels compete to select a representative node (RN). A representative node is chosen periodically from each channel which broadcasts information about its home channel onto rendezvous channel. The information consists of number of nodes on home channel, quiet period distribution and channel characteristics. Apart from QP and HCI, rendezvous channel comprises of rendezvous channel beacon (RCB) and contention based data transfer period. A RCB has a time slotted design, with total number of slots designated as t. During RCB, representative nodes (RN) switch to rendezvous channel and share information about their home channel. Each slot in RCB is designated to each RN, therefore $t = C + 2$; where 2 additional slots are required for new nodes joining the network.

Apart from QP and HCI, the superframe of a data channel comprises of home channel beacon (HCB) and data transfer period. During HCB, the RN returns from rendezvous channel to its home channel, and broadcasts the information it learned from other representative nodes in the network. A HCB on a channel has a time slotted architecture, where number of time-slots equals the number of nodes on that channel +1. An extra time slot is provided for a new node joining the network on that channel. Depending upon data channel type, the data transfer can be classified into two types: *reservation* and *contention* based data transfer. A reservation based channel (RBC) employs reservation based data transfer service, while a contention based channel (CBC) employs contention based data transfer service. RBC consists of ATIM (ad-hoc transfer indication message) period and reserve data slots. During ATIM period, communicating node performs contention, and reserve data slots ahead of actual data transmission. A three way handshake is performed during the reservation process. The reservation of a resource block before actual communication, allows implementation of higher priority service. The design of contiguous resource blocks allows provisioning of stream based services like voice or video which require contiguous stream of data transfer [2]. On the other hand contention data period on CBC requires nodes to perform a 4 way handshake similar to optional RTS/CTS mechanism of 802.11 [3]. Therefore nodes contend whenever they require to perform a data transfer during the contention data period. Contention based data transfer service is also followed by nodes on rendezvous channel.

5.2.1 Arbitration Interframe Spaces

For the purpose of packet prioritization, different arbitration interframe spaces are utilized. Arbitration interframe space is the time duration which a node has to wait before transmitting a packet. Arbitration in this discussed scheme is different from

Table 5.1 Interframe spaces for different packet types

Interframe space	RTS packet type/Other packet type	IFS_{min}	IFS_{mxo}
SIFS	Voice/CTS/ACK/DATA	IFS_{smin}	IFS_{smax}
MIFS	Video	IFS_{mmin}	IFS_{mmax}
IIFS	Best effort	IFS_{imin}	IFS_{imax}
LIFS	Background data	IFS_{lmin}	IFS_{lmax}

the traditional arbitration as in enhanced distributed channel access (EDCA) [4], where a fixed value is utilized and the value of contention window is changed on each retransmission. Here arbitration is defined as a random duration in [IFS_{min}, IFS_{max}]. Here $IFS_{max} = 2^r.IFS_{mxo}$, where r is the number of retransmission performed for this packet, and IFS_{mxo} is the initial maximal boundary for arbitration value selection. Each packet before transmission is assigned a counter which is initialized with the value of arbitration space. The counter is decremented whenever the channel is sensed to be free. If the counter reaches zero, the packet is transmitted. If transmission is unsuccessful, then the value of r is incremented and the packet is scheduled for retransmission. If the packet is not deliverable even after Γ number of retransmission, it is dropped. The value Γ is called as retry limit. Different limits of arbitration interframe space for different types of packets are shown in Table 5.1, in which S/M/I/L-IFS implies short, medium, intermediate and large interframe space respectively. Therefore an RTS packet of video has to wait MIFS duration before transmission. Similarly ACK packet of any data type has to wait for SIFS duration before transmission.

5.3 Initialization

The cognitive radio network initializes by selecting a rendezvous channel. A node in the network scans for a RCB while performing sensing on all *defined* channels. If a node does not detect any RCB, then it starts its own RCB by first selecting an appropriate channel as a rendezvous channel (RC). An auxiliary RC may also be selected as a backup, just in case main RC ceases to be free. If a node detects an existing RCB, it joins through by doing transmission on the extra time-slots of RCB. Based on the information it learned from RCB, it may join a data channel by following the same procedure on HCB. A node having high probability of performing a high priority data transmission will select reservation based channel. If there does not exist a data channel, the node may start its own beacon for the data channel. The node may classify a data channel as RBC or CBC depending upon channel availability. A channel having high availability is considered for the candidate of RBC and vice-versa.

5.4 Operation

Since two different types of data channels are utilized in the access scheme, two different etiquettes of channel access are also utilized. The nodes follow the etiquette of the channel in which they perform communication. The communication may take place on either of the home channels of communicating nodes. If the desired characteristics of communication media is not supported by either home channels of the communicating nodes, then the communication may take place on a foreign channel. In this case the etiquettes of the foreign channel will be utilized for communication purposes. Depending upon the channel characteristic and location (home channel) of sender and receiver, three different types of data transfer are classified:

5.4.1 Data Transfer on Reservation Based Channels

On a reservation based channel, nodes contend to reserve data slots during ATIM period. For contending, nodes employ *three* way handshake to reserve data slots ahead of actual communication. A node initiates this by sending first request-to-send (RTS) packet. The RTS packet of sender consists of a list identifying available data time-slots onto which the sender intends to communicate. The receiver replies with clear-to-send (CTS) packet containing the list of data time-slots on which it agrees to receive the data. The sender confirms this list by sending an acknowledgement (ACK). All other nodes know which *slots* are reserved for what *type* of data transfer. A high priority data transfer like voice or video can preempt the reserved data slots from scheduled low priority data transfer service; and therefore high priority service can schedule its own transmission in those reserved slots as if they are not reserved. During the reserved data period, scheduled nodes perform data communication.

5.4.2 Data Transfer on Contention Based Channels

Data transfer on a contention based channel follows the traditional optional 4 way handshake RTS/CTS mechanism of 802.11 [5]. A sender node initiates the transmission by sending an RTS packet containing the duration of the transmission in a field called as network allocation vector (NAV). The receiver replies with CTS containing NAV, to identify that it is ready to receive the data. The sender then performs transmission of DATA packets. After the reception of DATA packet, the receiver replies with an acknowledgement (ACK) packet.

5.4.3 Data Transfer on a Foreign Channel

If a sender has a packet for a receiver which does not lie on the home channel of the sender, the sender moves to the home channel of receiver after HCB. The sender then performs communication with the receiver using the channel etiquettes of the receiver. Once the communication is finished or HCI of the home channel of the sender starts, the sender moves back to its own home channel. The procedure is repeated until the receiver node decides to move onto the home channel of the sender.

If the desired characteristic of the channel is not supported by the home channel of receiver, then data transmission is performed on a foreign channel with the desired characteristics. The sender moves to the home channel of the receiver and sends a MOV packet to the receiver indicating the channel into which they should switch onto. If the receiver agrees, it replies with an acknowledgement MOV-ACK and immediately switches to the indicated channel. The sender after receiving the acknowledgement also switches to the indicated channel. Both sender and receiver node waits for LIFS duration on the indicated channel to overhear any current communication and then follow their etiquettes. Both sender and receiver move back to their home channel when the communication is finished or HCI of the home channels of sender/receiver starts.

5.5 Power Saving Mode Operation

The discussed MAC scheme allows different power saving mode operation for nodes depending upon their home channel. Nodes are always active during the period of beacon exchange (RCB, HCB, HCI) on their home channel. Here active duration refers to the time duration for transmit, receive or sensing operation.

On a reservation based channel, nodes are always active during HCB, ATIM, QP and HCI period. A node learns about the usage of channel (data slots) during ATIM period, and therefore schedules to enter into doze (idle) mode if it is not performing any communication. The node wakes up when it has its turn for sending or receiving data on reserved data time-slots. Figure 5.3 shows 3 nodes A, B and C operating on a reservation based channel. During ATIM period, nodes A and B have scheduled communication on data time-slots $S5 - S14$. At the end of ATIM, nodes A, B and C enter into doze mode. At the start of data slot $S5$, node A and B become active and perform communication. During QP, node A and B stop their transmission and perform sensing operation. During QP, node C wakes up and performs sensing operation. During HCI, all nodes exchange their beacon for the purpose of selection of a RN. Since node A and B are busy in performing data communication, some other node is chosen as RN. Once the communication is done, node A and B again enter into doze mode.

The power saving operation on contention based channel is followed similar to the power saving mode (PSM) of 802.11 [3]. All operating nodes on the channel

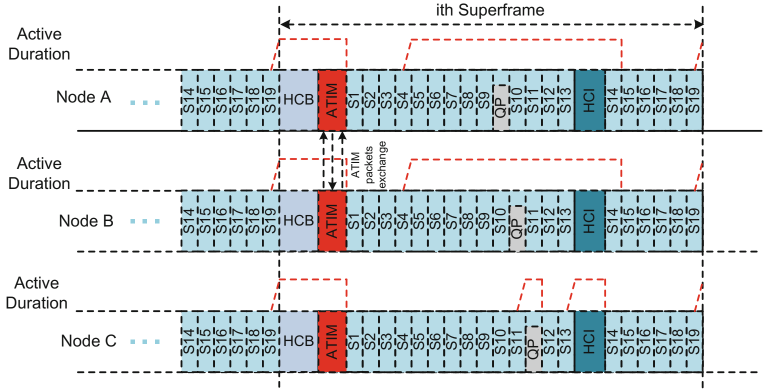


Fig. 5.3 Power saving mode operation on a reservation based channel of the MAC scheme

overhear the RTS and CTS packet of communicating nodes, which consists of a network allocation vector (NAV). Since NAV indicates the duration of transmission, all other nodes can calculate the time for which they should remain in doze mode. Therefore nodes sleep during an ongoing transmission of other nodes, and wake up when the transmission is finished. The value of NAV for RTS and CTS packet is calculated as:

$$NAV_{RTS} = t_{CTS} + t_{DATA} + t_{ACK}$$
$$NAV_{CTS} = t_{DATA} + t_{ACK}$$

where t_{pkt} is the time duration required for the transmission of a packet pkt.

5.6 Broadcast and Multicast Operation

Broadcast and multicast operation are required by many higher/lower layer protocols to implement certain functionality. Broadcast operation in multi-channel environment faces the problem of dissipation of a single packet over multiple channels and hence multiple channel hopping is required. The discussed scheme mitigates such a problem by providing a broadcast or multicast operation within 2 superframe. A node which has a packet to broadcast will select itself as a representative node and broadcast the packet in RCB of next superframe. The representative nodes from other channels on returning to their home channel from RCB will broadcast the packet in HCB, which allow all nodes on that channel to receive the broadcasted packet; since this follows on all channels, the broadcasted packet are received by all the nodes in the network. Multicast operation follows similar to the broadcast operation, except that a masking operation is required, which depends upon multicast application.

5.7 Performance Analysis

The discussed scheme is evaluated using a discrete event simulation in Matlab which simulates the network up to frame level. The channel availability model of Two-state Markov chain from Sect. 3.4.1 is utilized, with the channel state-transition probabilities, α and β set to 0.9 and 0.1 respectively. To clearly show the distinct performance on different data channel (RBC and CBC), the performance of each channel is individually evaluated. Users can make a decision on the basis of latency and throughput requirement to select an appropriate channel. Four different type of data packets are utilized: voice, video, best effort and background data. Two reservation based channel and two contention based channels are evaluated with 4 users on each channel.

On each channel, two senders are randomly selected from 4 users, while rest two as destination. The arrival rate of data packets on these users is modeled as Poisson arrival with the percentage distribution of aggregate arrival as voice, video, best effort and background data packets set as 10, 20, 60 and 10 % respectively. The parameters used for the simulation are shown in Table 5.2. To simplify the analysis, bandwidth of each channels is assumed to be equal and the size of RTS, CTS and ACK packets used on RBC and CBC are assumed to be equal. The data packet size of all 4 different data types are also assumed to be equal. To capture the effect of stream based transfer on RBC, a transmission of 3 voice packets requires only a single RTS/CTS/ACK handshake exchange during ATIM duration; similarly a transmission of 4 video packets requires only a single RTS/CTS/ACK handshake exchange during ATIM duration. While all other transmissions require exchange of RTS/CTS/ACK for every data packet. Similarly on CBC, all transmissions require exchange of RTS/CTS/ACK for every data packet. The arrival rate for each user is increased from 50 packets per second to 330 packets per second with step size of 20. The simulation time is 100 s, and each data point in the graph is the average of 100 run.

In Fig. 5.4, analysis of average latency of individual (in terms of priority) packets is done. A clear comparison of Fig. 5.4a, b evaluates that, packets on RBC has a low and defined (calculable) latency in comparison to CBC. Moreover the latency for voice and video packets in RBC does not increase as they tend to increase in CBC with increase in arrival rate. A calculable latency on RBC is attributed to its reservation based design, which allows data slots to be reserved ahead of actual communication. The main drawback of RBC etiquette in comparison to CBC is that, it has a high latency for low level priority packets.

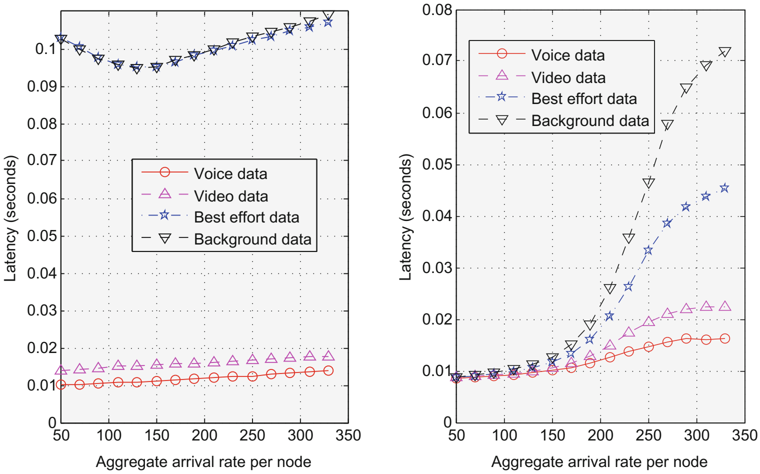
Figure 5.5 shows the probability of success of transmission of each originating packet. From Fig. 5.5a, b, it can be concluded that as the arrival rate increases, there is a decrease in success probability due to more number of collisions. Also the success ratio of RBC for higher priority packets (voice and video) is more in comparison to CBC. This can be attributed to pre-scheduled DATA packets in RBC, where as in CBC, large DATA packets result in backoff or collision of other packets. The success ratio of low priority (best effort and background) data packets is lower in RBC due

Table 5.2 Simulation parameters

Parameters	Value
Simulation time	100 s
Slot time	10 μs
Number of RBC	2
Number of CBC	2
Bandwidth of channels	2 Mbps
Superframe size	100 ms
RCB beacon size	15 ms
HCB beacon size	3 ms
HCI beacon size	2 ms
Quiet period size	2.5 ms
ATIM window size	35 ms
Number of reserved data slots	24
Reserved data time slot size	2.5 ms
RTS packet size	240 bits
CTS packet size	240 bits
ACK packet size	240 bits
DATA packet size	5000 bits
IFS_{smin}, IFS_{mmin}	1
IFS_{smin}, IFS_{mmin}	1
IFS_{imin}, IFS_{lmin}	3
IFS_{smax}	3
IFS_{mmax}	5
IFS_{imax}	7
IFS_{lmax}	10
Γ	5

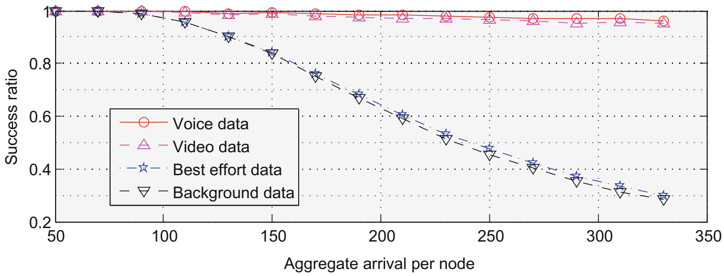
to the preemptive nature of high priority packets to take away the communication segments (data slots) reserved for low priority packets.

Figure 5.6 shows the channel utilization of RBC and CBC. Here, the channel utilization is calculated on the basis of actual DATA packets transmitted. Therefore, the channel utilization does not include packets like RTS, CTS or ACK. At low arrival rate, RBC tends to perform better due to low collision in ATIM contention window. The lower collision is attributed to small size of control packets, where actual large DATA packets are communicated during reserved data slots. But after a threshold (aggregate number of arrivals per node = 170), CBC performs better in terms of channel utilization. This is attributed to restricted contention window size in RBC. The small ATIM contention window in RBC cannot accommodate more than a defined number of control packets, and hence actual communication is limited by it. Therefore, CBC achieves a higher channel utilization due to large contention based data transfer period.

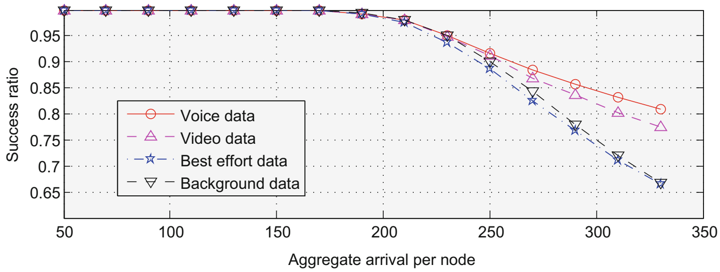


a: Reservation based channel b: Contention based channel

Fig. 5.4 Latency of packets on different channels



a: Reservation based channel



b: Contention based channel

Fig. 5.5 Success ratio of packets on different channels

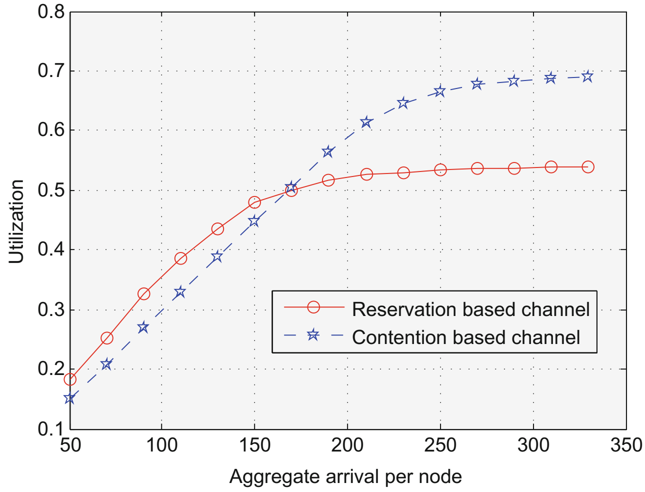


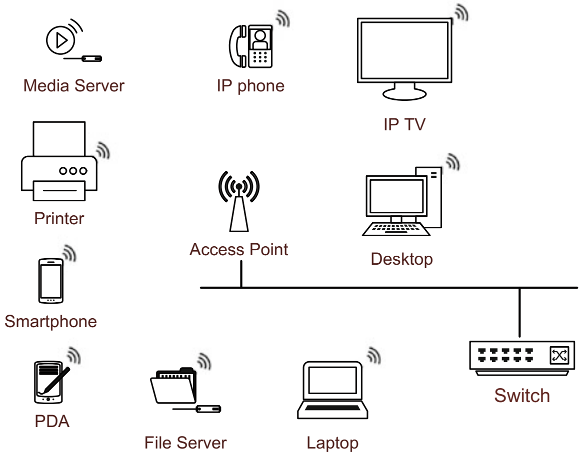
Fig. 5.6 Channel utilization

5.8 Infrastructure Mode Operation

The discussed scheme can also be employed in infrastructure mode by doing slight modification in middleware without any change on hardware requirements of users node. For operation in infrastructure mode, network employs an access point (AP) with the number of transceivers equal to the number of data channels employed. Data channels are formulated by AP with quiet periods distributed in a predefined sequence. The requirement of a rendezvous channel is removed and the AP acts as a *gateway* to all the nodes operating in the network. Access point acts as representative node (RN) on all data channels and the requirement of home channel information (HCI) beacon is also removed. Therefore all data channels (including RBC and CBC) are synchronized, and overlap with each other. During HCB, AP learns about the number of active nodes on a channel, channel characteristics and information regarding channel sensing from different nodes to perform cooperative sensing. Any node that wants to send a packet to another node, passes it through access point. Therefore user nodes do not hop for packet transmission. An AP also calculates and broadcasts average latency of packets on a given channel, so that a node can join/move to a given channel depending upon the observed latency. Nodes join/leave a channel through the help of AP; while AP also coordinates in assignment/removal of beacon slot for users node in HCB.

The infrastructure mode, operation of the discussed MAC scheme is shown in Fig. 5.7, where different equipments in home/office with different priority services operate with each other. An access point acts as a *gateway* and allows Internet connection through a *switch*. High priority services like IP phone and smartphone will operate with voice/video priority services. IP TV and media servers will operate with

Fig. 5.7 Infrastructure mode operation with network equipments



video priority but laptops and desktop will operate with hybrid priority (video and best effort) depending upon latency requirement, file servers and PDA will operate with best effort priority; while printers will operate with background priority.

In infrastructure mode, all nodes are connected to the AP, and hence are not hidden from it. Nodes may be hidden from each other, due to location and transmission power constraints. Since nodes perform three way or four way data exchange (depending upon channel type), the hidden terminal problem is solved.

5.9 Hidden Terminal Problem in Ad-hoc Mode

The discussed access scheme in ad-hoc mode is only defined for a network consisting of single-hop nodes. In multi-hop scenario, it may be possible that the information broadcasted by a rendezvous node (RN) is not be heard by some nodes on that channel due to the difference in location. Similarly, the information transmitted by some nodes on home channel beacon may not be heard by other home nodes. This is called hidden terminal problem, which results in nodes having inconsistent set of information. Multiple solutions exist to solve this problem. One solution is to increase the size of home beacon and ask every home node to repeat the information it learned from RN and other home nodes; therefore the information broadcasted is cumulative in nature. A node which is hidden to RN or to any other node, will overhear it and thus they all will have consistent set of information. Another solution is that all nodes generate its next-hop neighbor list. A next hop neighbor list of a *node* consists of list of neighbor nodes that the *node* learns from overhearing packets on the channel. This next hop neighbor list is matched with the information broadcast on HCB. If there are inconsistencies among the list of visible nodes on the channel, they are resolved.

5.10 Discussion

In a cognitive radio network, multiple cognitive nodes try to access sporadically varying resources (frequency spectrum) which results in access collision. To mitigate access collision, an access scheme is required which is followed by all the cognitive nodes operating in the cognitive radio network. The etiquettes of an access scheme is directly responsible for quality of service from latency perspective, while it is also responsible for quality of service from throughput perspective to an extent. The queuing delay which directly affects latency is controlled by the access scheme while throughput is directly controlled by the channel selection scheme and indirectly by the design of media access scheme.

In this chapter, different media access schemes for cognitive radio networks were discussed and a case study was performed on a QoS aware hybrid media access scheme framework for cognitive radio network. The scheme utilizes a hybrid of two different channel etiquettes: reservation based channel and contention based channel. These channels have different attributes and hence support different types of services. The discussed media access scheme utilizes power saving mode for doze mode operation while supporting major network operations like broadcast and multicast. An infrastructure based operation is also discussed which requires slight modification on middleware, while no changes are required on hardware of user node. Hidden terminal problems in infrastructure mode and ad-hoc mode are also discussed. Performance analysis of the discussed scheme shows that reservation based channels have low latency and higher transmission success probability for higher priority services. In contrast, the channel utilization of contention based channel achieves better performance than that of the reservation based channel for higher arrival rate. Even though a media access scheme mitigates access collisions within a network, it cannot directly mitigate access collision with another network.

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