release the token, then some recovery procedure must be invoked to get the token back in circulation. Over the years many token-passing protocols have been developed, including the fiber distributed data interface (FDDI) protocol [Jain 1994] and the IEEE 802.5 token ring protocol [IEEE 802.5 2012], and each one had to address these as well as other sticky issues.

5.3.4 DOCSIS: The Link-Layer Protocol for Cable Internet Access

In the previous three subsections, we've learned about three broad classes of multiple access protocols: channel partitioning protocols, random access protocols, and taking turns protocols. A cable access network will make for an excellent case study here, as we'll find aspects of *each* of these three classes of multiple access protocols with the cable access network!

Recall from Section 1.2.1, that a cable access network typically connects several thousand residential cable modems to a cable modem termination system (CMTS) at the cable network headend. The Data-Over-Cable Service Interface Specifications (DOCSIS) [DOCSIS 2011] specifies the cable data network architecture and its protocols. DOCSIS uses FDM to divide the downstream (CMTS to modem) and upstream (modem to CMTS) network segments into multiple frequency channels. Each downstream channel is 6 MHz wide, with a maximum throughput of approximately 40 Mbps per channel (although this data rate is seldom seen at a cable modem in practice); each upstream channel has a maximum channel width of 6.4 MHz, and a maximum upstream throughput of approximately 30 Mbps. Each upstream and downstream channel is a broadcast channel. Frames transmitted on the downstream channel by the CMTS are received by all cable modems receiving that channel; since there is just a single CMTS transmitting into the downstream channel, however, there is no multiple access problem. The upstream direction, however, is more interesting and technically challenging, since multiple cable modems share the same upstream channel (frequency) to the CMTS, and thus collisions can potentially occur.

As illustrated in Figure 5.14, each upstream channel is divided into intervals of time (TDM-like), each containing a sequence of mini-slots during which cable modems can transmit to the CMTS. The CMTS explicitly grants permission to individual cable modems to transmit during specific mini-slots. The CMTS accomplishes this by sending a control message known as a MAP message on a downstream channel to specify which cable modem (with data to send) can transmit during which mini-slot for the interval of time specified in the control message. Since mini-slots are explicitly allocated to cable modems, the CMTS can ensure there are no colliding transmissions during a mini-slot.

But how does the CMTS know which cable modems have data to send in the first place? This is accomplished by having cable modems send mini-slot-request frames to the CMTS during a special set of interval mini-slots that are dedicated

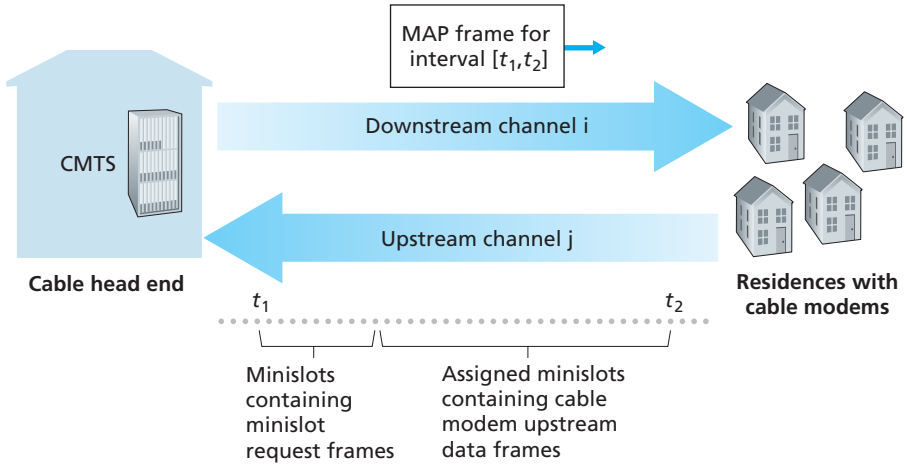

Figure 5.14 ♦ Upstream and downstream channels between CMTS and cable modems

for this purpose, as shown in Figure 5.14. These mini-slot-request frames are transmitted in a random access manner and so may collide with each other. A cable modem can neither sense whether the upstream channel is busy nor detect collisions. Instead, the cable modem infers that its mini-slot-request frame experienced a collision if it does not receive a response to the requested allocation in the next downstream control message. When a collision is inferred, a cable modem uses binary exponential backoff to defer the retransmission of its mini-slot -request frame to a future time slot. When there is little traffic on the upstream channel, a cable modem may actually transmit data frames during slots nominally assigned for mini-slot-request frames (and thus avoid having to wait for a mini-slot assignment).

A cable access network thus serves as a terrific example of multiple access protocols in action—FDM, TDM, random access, and centrally allocated time slots all within one network!

5.4 Switched Local Area Networks

Having covered broadcast networks and multiple access protocols in the previous section, let's turn our attention next to switched local networks. Figure 5.15 shows a switched local network connecting three departments, two servers and a router with four switches. Because these switches operate at the link layer, they switch link-layer frames (rather than network-layer datagrams), don't recognize