

Selective Repeat (SR)

The GBN protocol allows the sender to potentially "fill the pipeline" in "Pipelined Reliable Data Transfer Protocols" Figure 2 with packets, therefore avoiding the channel utilization problems we noted with stop-and-wait protocols. There are, on the other hand, scenarios in which GBN itself suffers from problems. Particularly, when the window size and bandwidth-delay product are both large, many packets can be in the pipeline. A single packet error can thus cause GBN to retransmit a large number of packets, many unnecessarily. As the probability of channel errors increases, the pipeline can become filled with

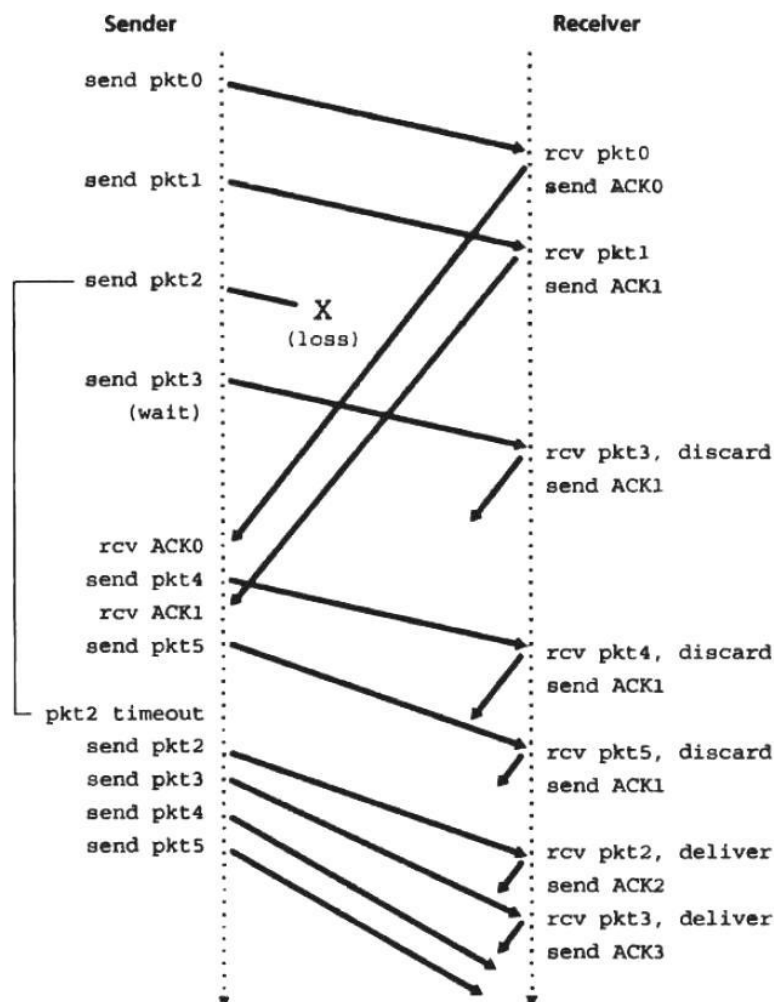


Figure 1. Go-Back-N in operation

these unnecessary retransmissions. Imagine, in our message-dictation scenario, that if every time a word was garbled, the surrounding 1,000 words (for instance, a window size of 1,000 words) had to be repeated. The dictation would be slowed by all of the reiterated words.

As the name suggests, selective-repeat protocols avoid unnecessary retransmissions by having the sender retransmit only those packets that it suspects were received in error (that is, were lost or corrupted) at the receiver. This individual, as-needed, retransmission will require that the receiver individually acknowledge correctly received packets. A window size of N will again be used to limit the number

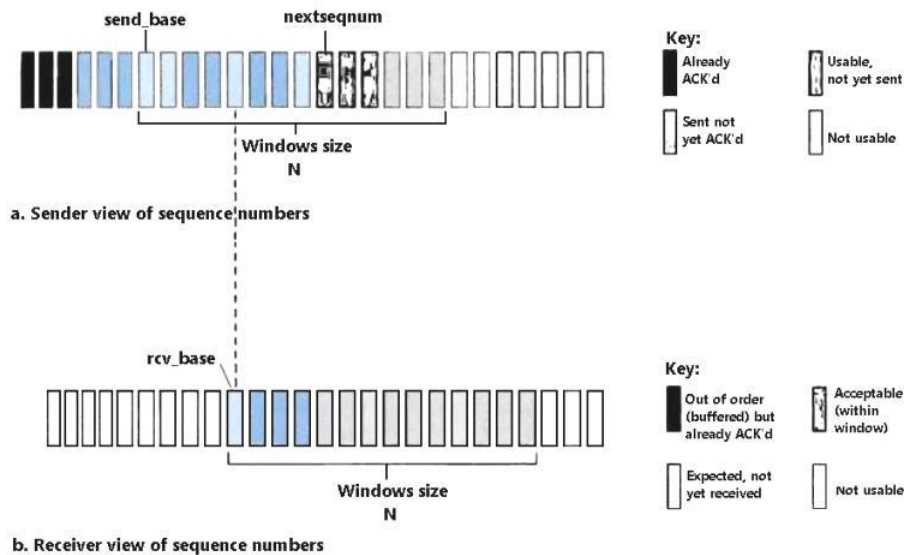


Figure 2. Selective-repeat (SR) sender and receiver views of sequence-number space

of outstanding, unacknowledged packets in the pipeline. However, unlike GBN, the sender will have already received ACKs for some of the packets in the window. Figure 2 shows the SR sender's view of the sequence number space. Figure 3 details the various actions taken by the SR sender.

The SR receiver will acknowledge a correctly received packet whether or not it is in order. Out-of-order packets are buffered until any missing packets (that is, packets with lower sequence numbers) are received, at which point a batch of packets can be delivered in-order to the upper layer. Figure 4 itemizes the various actions taken by the SR receiver. Figure 5 shows an example of SR operation in the presence of lost packets. Note that in Figure 5, the receiver initially buffers packets 3, 4 and 5 and delivers them together with packet 2 to the upper layer when packet 2 is finally received.

It is important to note that in Step 2 in Figure 4, the receiver reacknowledges (rather than ignores) already received packets with certain sequence numbers below the current window base. You should convince yourself that this reacknowledgment is indeed needed. Given the sender and receiver sequence number spaces in Figure 2, for instance, if there is no ACK for packet `send_base` propagating from the receiver to the sender, the sender will ultimately retransmit packet `send_base`, even though it is clear (to us, not the sender!) that the receiver has already received

1. Data received from above. When data is received from above, the SR sender checks the next available sequence number for the packet. If the sequence number is within the sender's window, the data is packetized and sent; otherwise it is either buffered or returned to the upper layer for later transmission, as in GBN.
2. Timeout. Timers are again used to protect against lost packets. However, each packet must now have its own logical timer, since only a single packet will be transmitted on timeout. A single hardware timer can be used to mimic the operation of multiple logical timers [Varghese 1997].
3. ACK received. If an ACK is received, the SR sender marks that packet as having been received, provided it is in the window. If the packet's sequence number is equal to `send_base`, the window base is moved forward to the unacknowledged packet with the smallest sequence number. If the window moves and there are untransmitted packets with sequence numbers that now fall within the window, these packets are transmitted.

Figure 3. SR sender events and actions

1. Packet with sequence number in $[rcv_base, rcv_base+N-1]$ is correctly received. In this case, the received packet falls within receiver's window and a selective ACK packet is returned to the sender. If the packet was not previously received, it is buffered. If this packet has a sequence number equal to the base of the receive window (`rcv_base` in Figure 1), then this packet, and any previously buffered and consecutively numbered (beginning with `rcv_base`) packets are delivered to the upper layer. The receive window is then moved forward by the number of packets delivered to the upper layer. As an example, look at Figure 5. When a packet with a sequence number of `rcv_base=2` is received, it and packets 3,4 and 5 can be delivered to the upper layer.
2. Packet with sequence number in $[rcv_base-N, rcv_base-1]$ is correctly received. In this case, an ACK must be generated, even though this is a packet that the receiver has previously acknowledged.
3. Otherwise. Ignore the packet.

Figure 4. SR receiver events and actions

that packet. If the receiver were not to acknowledge this packet, the sender's window would never move forward. This example illustrates an important aspect of SR protocols (and many other protocols as well). The sender and receiver will not always have an identical view of what has been received correctly and what has not. For SR protocols, this means that the sender and receiver windows will not always coincide.

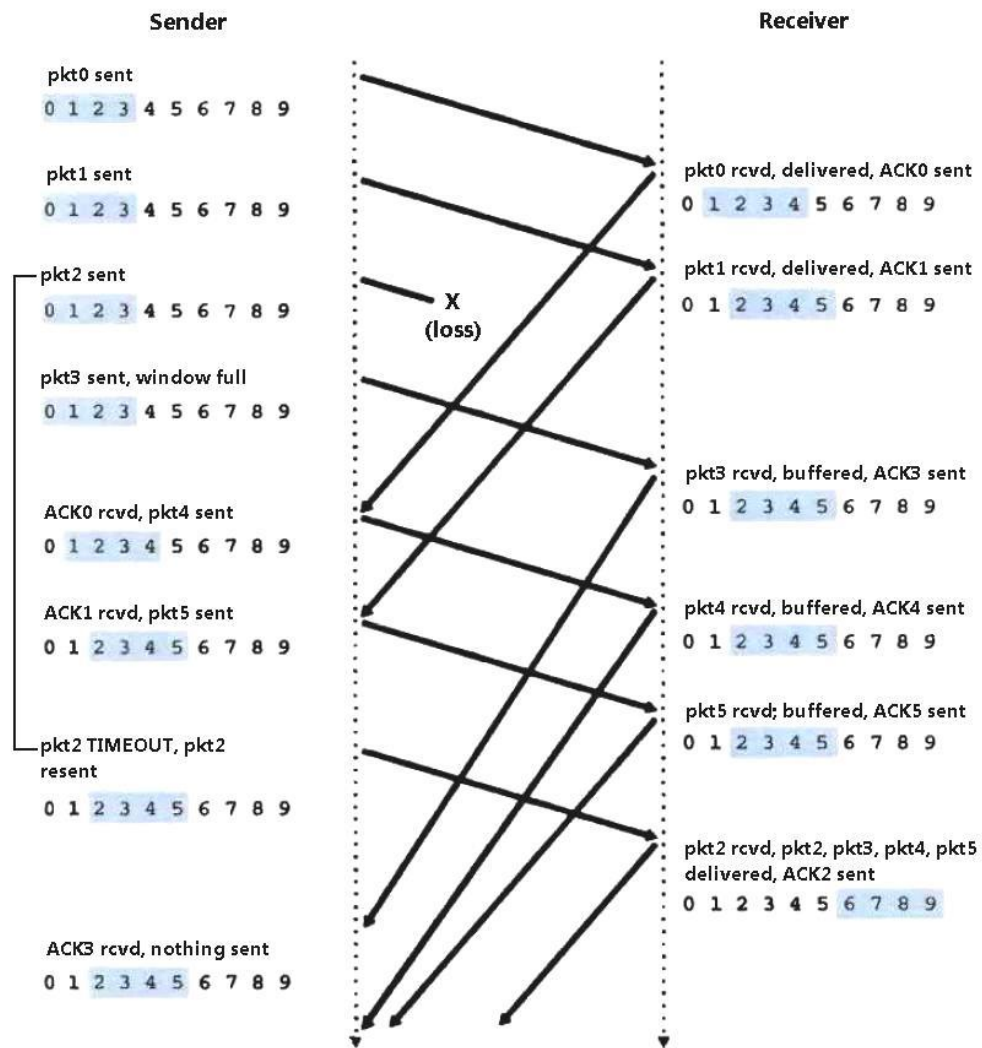
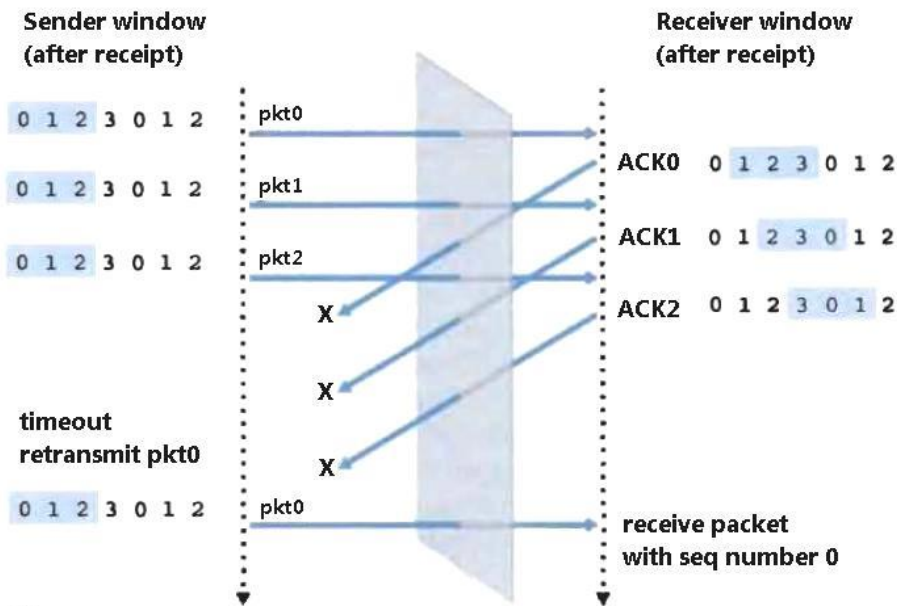
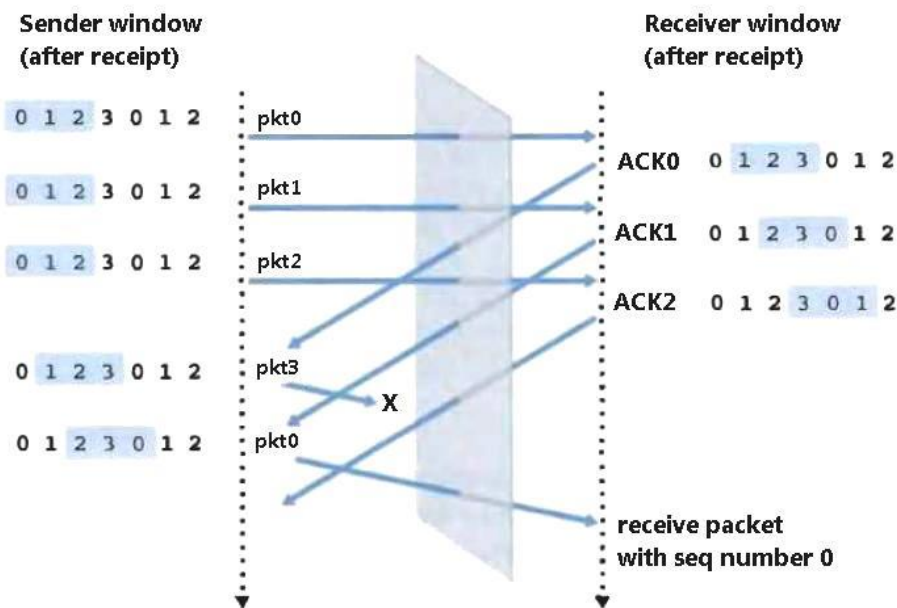


Figure 5. SR operation

The lack of synchronization between sender and receiver windows has important consequences when we are faced with the reality of a finite range of sequence numbers. Consider what could happen, for example, with a finite range of four packet sequence numbers, 0,1,2,3 and a window size of three. Suppose packets 0 through 2 are transmitted and correctly received and acknowledged at the receiver. At this point, the receiver's window is over the fourth, fifth and sixth packets, which have sequence numbers 3,0 and 1, respectively. Now consider two scenarios. In the first scenario, shown in Figure 6(a), the ACKs for the first three packets are lost and



a.



b.

**Figure 6. SR receiver dilemma with too-large windows:
 A new packet or a retransmission**

the sender retransmits these packets. The receiver thus next receives a packet with sequence number 0 - a copy of the first packet sent.

In the second scenario, shown in Figure 6(b), the ACKs for the first three packets are all delivered correctly. The sender thus moves its window forward and sends the fourth, fifth, and sixth packets, with sequence numbers 3,0 and 1, respectively. The packet with sequence number 3 is lost, but the packet with sequence number 0 arrives - a packet containing new data.

Now consider the receiver's viewpoint in Figure 6, which has a figurative curtain between the sender and the receiver, since the receiver cannot "see" the actions taken by the sender. All the receiver observes is the sequence of messages it receives from the channel and sends into the channel. As far as it is concerned, the two scenarios in Figure 6 are identical. There is no way of distinguishing the retransmission of the first packet from an original transmission of the fifth packet. Clearly, a window size that is 1 less than the size of the sequence number space won't work. The window size must be less than or equal to half the size of the sequence number space for SR protocols.

This completes our discussion of reliable data transfer protocols. We've covered a lot of ground and introduced various mechanisms that together provide for reliable data transfer. Table 1 summarizes these mechanisms. Now that we have seen all of these mechanisms in operation and can see the "big picture", we encourage you to review this section again to see how these mechanisms were incrementally added to cover increasingly complex (and realistic) models of the channel connecting the sender and receiver, or to improve the performance of the protocols.

Let's end our discussion of reliable data transfer protocols by considering one remaining assumption in our underlying channel model. Recall that we have assumed that packets cannot be reordered within the channel between the sender and receiver. This is usually a reasonable assumption when the sender and receiver are connected by a single physical wire. On the other hand, when the "channel" connecting the two is a network, packet reordering can occur. One manifestation of packet reordering is that old copies of a packet with a sequence or acknowledgment number of x can appear, even though neither the sender's nor the receiver's window contains x . With packet reordering, the channel can be thought of as essentially buffering packets and spontaneously emitting these packets at any point in the future. Because sequence numbers may be reused, some care must be taken to guard against such duplicate packets. The approach taken in practice is to ensure that a sequence number is not reused until the sender is "sure" that any previously sent packets with sequence number x are no longer in the network. This is done by assuming that a packet cannot "live" in the network for longer than some fixed maximum amount of time. A maximum packet lifetime of approximately three minutes is assumed in the TCP extensions for high-speed networks. Sunshine 1978 describes a method for using sequence numbers such that reordering problems can be completely avoided.

Mechanism	Use, Comments
Checksum	Used to detect bit errors in a transmitted packet.
Timer	Used to timeout/retransmit a packet, possibly because the packet (or its ACK) was lost within the channel. Because timeouts can occur when a packet is delayed but not lost (premature timeout), or when a packet has been received by the receiver but the receiver-to-sender ACK has been lost, duplicate copies of a packet may be received by a receiver.
Sequence number	Used for sequential numbering of packets of data flowing from sender to receiver. Gaps in the sequence numbers of received packets allow the receiver to detect a lost packet. Packets with duplicate sequence numbers allow the receiver to detect duplicate copies of a packet.
Acknowledgment	Used by the receiver to tell the sender that a packet or set of packets has been received correctly. Acknowledgments will typically carry the sequence number of the packet or packets being acknowledged. Acknowledgments may be individual or cumulative, depending on the protocol.
Negative acknowledgment	Used by the receiver to tell the sender that a packet has not been received correctly. Negative acknowledgments will typically carry the sequence number of the packet that was not received correctly.
Window, pipelining	The sender may be restricted to sending only packets with sequence numbers that fall within a given range. By allowing multiple packets to be transmitted but not yet acknowledged, sender utilization can be increased over a stop-and-wait mode of operation. We'll see shortly that the window size may be set on the basis of the receiver's ability to receive and buffer message, or the level of congestion in the network, or both.

Table 1. Summary of reliable data transfer mechanisms and their use