UNIT-3

Data Link Layer: - The Data Link Layer - Services Provided to the Network Layer – Framing – Error Control – Flow Control, Error Detection and Correction – Error-Correcting Codes – Error Detecting Codes, Elementary Data Link Protocols- A Utopian Simplex Protocol-A Simplex Stop and Wait Protocol for an Error free channel-A Simplex Stop and Wait Protocol for a Noisy Channel, Sliding Window Protocols-A One Bit Sliding Window Protocol-A Protocol Using Go-Back-NA Protocol Using Selective Repeat

DATA LINK LAYER DESIGN ISSUES

DATA LINK LAYER

The data link layer has a number of specific functions it can carry out. These functions include

1. Providing a well-defined service interface to the network layer.
2. Provides services for the reliable interchange of data across a data link established by the physical layer.
3. Link layer protocols manage the establishment, maintenance, and release of data-link connections.
4. Data-link protocols control the flow of data, dealing with transmission errors, and supervise data error recovery.
5. Regulating the flow of data so that slow receivers are not swamped by fast senders.
6. Recovery from abnormal conditions.

To accomplish these goals, the data link layer takes the packets it gets from the network layer and encapsulates them into frames for transmission. Each frame contains a frame header, a payload field for holding the packet, and a frame trailer, as illustrated in Fig. 2-1. Frame management forms the heart of what the data link layer does.

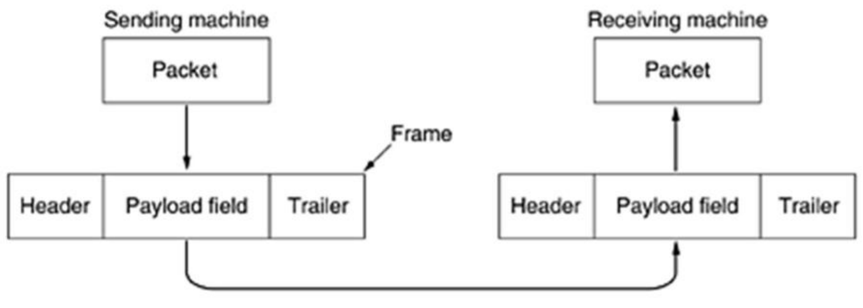


Figure 2-1. Relationship between packets and frames.

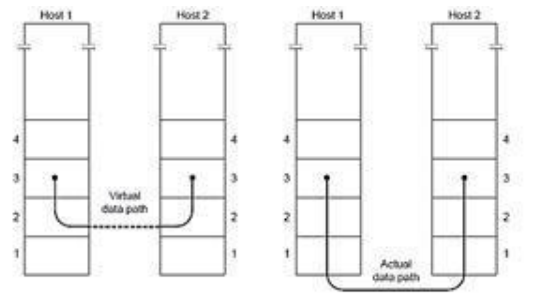
Data Link Layer Design Issues

1. Providing a well-defined service interface to the network layer
2. Determining how the bits of the physical layer are grouped into frames
3. Dealing with transmission errors
4. Regulating the flow of frames so that slow receivers are not swamped by fast senders.

1. Services Provided to the Network Layer

- The function of the data link layer is to provide service to the network layer.
- The principal service is transferring data from the network layer on the source machine to the network layer on the destination machine.
- The network layer hands some bits to the data link layer for transmission to the destination, the job of the data link layer is to transmit the bits to the destination machine, so they can be handed over to the network layer on the destination machine.

The job of the data link layer is to transmit the bits to the destination machine so they can be handed over to the network layer there, as shown in Fig.(a). The actual transmission follows the path of Fig.(b), but it is easier to think in terms of two data link layer processes communicating using a data link protocol.



(a) Virtual communication. (b) Actual communication.

- The data link layer can be designed to offer various services, Three possibilities that are commonly provided are:

1. Unacknowledged connectionless service.

2. Acknowledged connectionless service.

3. Acknowledged connection-oriented service.

Unacknowledged connectionless service

Unacknowledged connectionless service consists of having the source machine send independent frames to the destination machine without having the destination machine acknowledge them. No connection is established beforehand or released afterward. Good channels with low eror rates, for real-time traffic, such as speech.

Acknowledged connectionless service

When this service is offered, there are still no connections used, but each frame sent is individually acknowledged. This way, the sender knows whether or not a frame has arrived safely. Good for unreliable channels, such as wireless.

Acknowledged connection-oriented service

With this service, the source and destination machines establish a connection before any data are transferred. Each frame sent over the connection is numbered, and the data link layer guarantees that each frame sent is received. Furthermore, it guarantees that each frame is received exactly once and that all frames are received in the right order.

When connection-oriented service is used, transfers have three distinct phases.

1. In the first phase the connection is established by having both sides initialize variable and counter need to keep track of which frames have been received and which ones have not.
2. In the second phase, one or more frames are actually transmitted.
3. In the third phase, the connection is released, freeing up the variables, buffers, and other resources used to maintain the connection.

2. Framing

- In order to provide service to the network layer, the data link layer must use the service provided to it by the physical layer.
- What the physical layer does is accept raw bit stream and attempt to deliver it to the destination. This bit stream is not guaranteed to be error free.
- It is up to the data link layer to detect, and if necessary, correct errors.
- The usual approach is for the data link layer to break the bit stream up into discrete frames and compute the checksum for each frame. When the frames arrive at the destination , the checksum is re-computed.

There are four methods of breaking up the bit stream

1. Character count.
2. Starting and ending character stuffing.
3. Starting and ending flags, with bit stuffing.
4. Physical layer coding violations.

Character count, uses a field in the header to specify the number of characters in the frame. When the data link layer at the destination sees the character count, it knows how many characters follow. Problem: count can possible be misrepresented by a transmission error. This method is rarely used anymore.

Starting and ending character stuffing, gets around the problem of resynchronization after an error by having each frame start with the ASCII character sequence DLE STX and end with the sequence DLE ETX. (DLE is Data Link Escape, STX is Start of Text, and ETX is End of Text). **Problem:** a serious problem occurs with this method when binary data, such as object programs or floating-point numbers, are being transmitted it is possible that the DLE, STX, and ETX characters can occur, which will interfere with the framing. One way to solve this problem is to have the sender's data link layer insert and DLE character just before each "accidental" DLE and the data link layer on the other machine removes them before it gives the data to the network layer, this is called Character stuffing.

Starting and ending flags with bit stuffing, allows data frames to contain and arbitrary number of bits and allows character codes with an arbitrary number of bits per character. Each frame begins and ends with a special bit pattern, 01111110, called a flag byte. Whenever the sender's data link layer encounters five consecutive ones in the data, it automatically stuffs a 0 bit into the outgoing bit stream, which is called bit stuffing. The receiving machine destuffs the 0 bit. • The fourth method, Physical coding violations, is only applicable to networks in which the encoding on the physical medium contains some redundancy. For example, some LANs encode 1 bit of data by using 2 physical bits.

3. **Error Control**
   - The next problem to deal with is to make sure all frames are eventually delivered to the network layer at the destination, and in proper order.
   - The usual way to ensure reliable delivery is to provide the sender with some feedback about what is happening at the other end of the line.
   - One complication with this is that the frame may vanish completely, in which case, the receiver will not react at all, since it has no reason to react.
   - This possibility is dealt with by introducing timers into the data link layer. When the sender transmits a frame, it generally also starts a timer. The timer is set to go off after an interval long enough for the frame to reach the destination machine. If the frame or acknowledgment is lost the timer will go off. The obvious solution is to transmit the frame again. This creates the problem of possible sending frames multiple times. To prevent this from happening, it is generally necessary to assign sequence numbers to outgoing frames, so that the receiver can distinguish retransmission from originals.
   - The whole issue of managing the timers and sequence numbers so as to ensure that each frame is ultimately passed to the network layer at the destination exactly one, no more no less, is an important part of the data link layer's duties.

4. **Flow Control**
   - Another important design issue that occurs in the data link layer (and higher layers as well) is what to do with a sender that systematically wants to transmit frames faster than a receiver can accept them.
   - This situation can easily occur when the sender is running on a fast computer and the receiver is running on a slow machine.
   - The usual solution is to introduce flow control to throttle the sender into sending no faster than the receiver can handle the traffic.
   - Various flow control schemes are known, but most of them use the same basic principle, eg HDLC. The protocol contains well-defined rules about when a sender may transmit the next frame.

ERROR DETECTION AND CORRECTION

Error sources are present when data is transmitted over a medium. Even if all possible error-reducing measures are used during the transmission, an error invariably creeps in and begins to disrupt data transmission. Any computer or communication network must deliver accurate messages.

Error detection is applied mostly in the data-link layer but is also performed in other layers. In some cases, the transport layer includes some sort of error-detection scheme. When a packet arrives at the destination, the destination may extract an error-checking code from the transport header and perform error detection. Sometimes, network-layer protocols apply an error-detection code in the network-layer header. In this case, the error detection is performed only on the IP header, not on the data field. At the application layer, some type of error check, such as detecting lost packets, may also be possible. But the most common place to have errors is still the data-link layer. Possible and common forms of errors at this level are described here and are shown in Figure 2.1

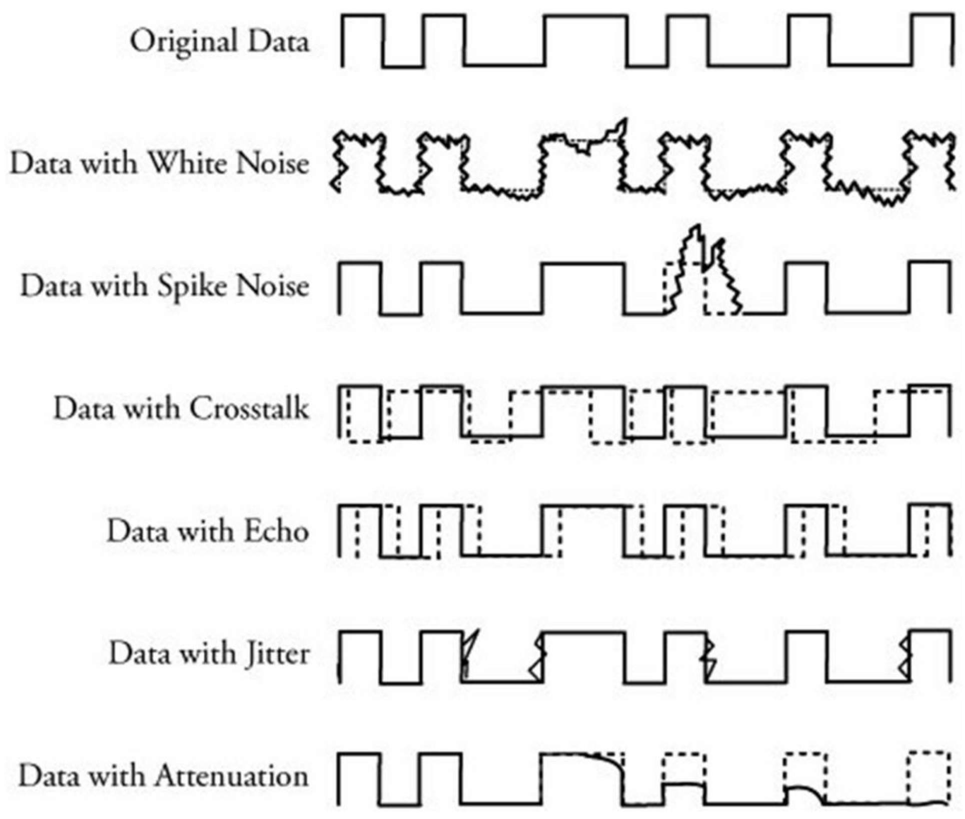


Figure 2.1. Common forms of data errors at the data-link level

Networks must be able to transfer data from one device to another with complete accuracy. Data can be corrupted during transmission. For reliable communication, errors must be detected and corrected.

TYPES OF ERRORS

Whenever bits flow from one point to another, they are subject to unpredictable changes because of interference. This interference can change the shape of the signal; leads to an error in data transmission. Basic types of errors are

i. Single-Bit Error
ii. Burst Error

i. Single-Bit Error

The term single-bit error means that only one bit of a given data unit (such as a byte, character, data unit, or packet) is changed from 1 to 0 or from 0 to I. In a single-bit error, only one bit in the data unit has changed.

Figure 2.1 shows the effect of a single-bit error on a data unit. To understand the impact of the change, imagine that each group of 8 bits is an ASCII character with a 0 bit added to the left. In the figure, 00000010 (ASCII STX) was sent, meaning start of text, but 00001010 (ASCII LF) was received, meaning line feed.

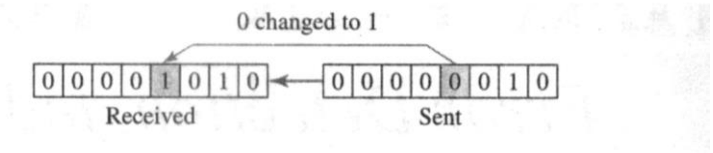


Fig 2.1 Single-bit error

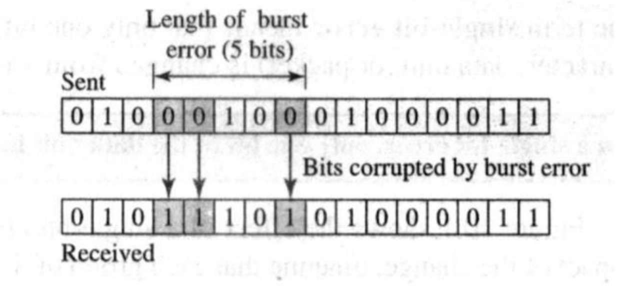
Single-bit errors are the least likely type of error in serial data transmission. To understand Why, imagine a sender sends data at 1 Mbps means that each bit lasts only 1/1,000,000 s, or 1 µs. For a single-bit error to occur, the noise must have a duration of on1y 1 µs, which is very rare; noise normally lasts much longer than this.

However, a single-bit error can happen if we are sending data using parallel transmission. For example, if eight wires are used to send all 8 bits of 1 byte at the same time and one of the wires is noisy, one bit can be corrupted in each byte. Think of parallel transmission inside a computer, between CPU and memory, for example.

ii. Burst Error

The term burst error means that 2 or more bits in the data unit have changed from 1 to 0 or from 0 to 1.

Figure below shows the effect of a burst error on a data unit. In this case, 0100010001000011 was sent, but 0101110101000011 was received. Note that a burst error does not necessarily mean that the errors occur in consecutive bits. The length of the burst is measured from the first corrupted bit to the last corrupted bit. Some bits in between may not been corrupted.



Burst error is most likely to occur in a serial transmission. The duration of noise is normally longer than the duration of one bit, which means that when noise affects data, it affects a set of bits. The number of bits affected depends on the data rate and duration of noise. For example, if we are sending data at 1 Kbps, a noise of 1/100 s can affect 10 bits; if we are sending data at 1 Mbps, the same noise can affect 10,000 bits.

ERROR DETECTION

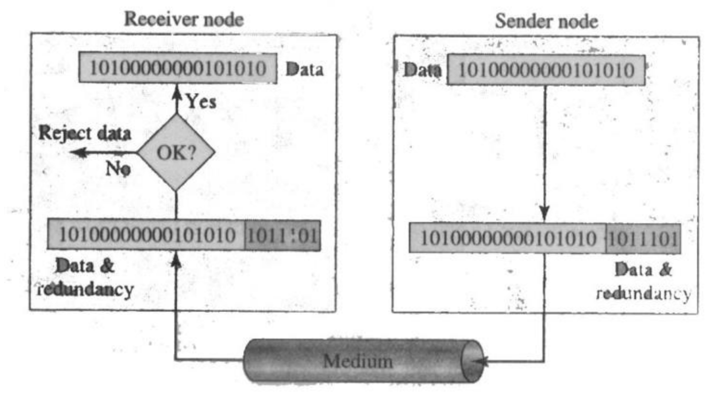
Most networking equipment at the data-link layer inserts some type of error-detection code. When a frame arrives at the next hop in the transmission sequence, the receiving hop extracts the error-detection code and applies it to the frame. When an error is detected, the message is normally discarded. In this case, the sender of the erroneous message is notified, and the message is sent again. However, in real-time applications, it is not possible to resend messages. The most common approaches to error detection are

Redundancy

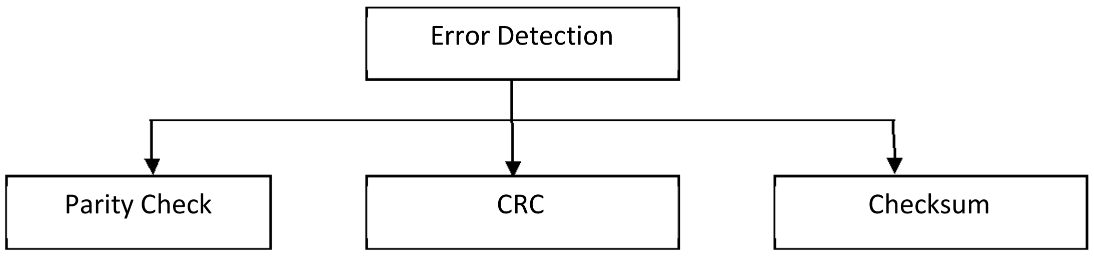
One error detection mechanism would be to send every data unit twice. The receiving device would then able to do a bit for bit comparison between the two versions of the data. Any discrepancy would indicate an error, and an appropriate correction mechanism could be set in place The system would be completely accurate (the odds of errors being introduced on to exactly the same bits in both sets of data are infinitesimally small), but it would also Not only would the transmission time double, but also the time it takes to compare every unit bit by bit must be added.

Error detection uses the concept of redundancy, which means adding extra bits for detecting errors at the destination.. This technique is called redundancy because the extra bits are redundant to the information; they are discarded as soon as the accuracy of the transmission has been determined.

Figure 1.3 shows the process of using redundant bits to check the accuracy of a data unit. Once the data stream has been generated, it passes through a device that analyzes it and adds on an appropriately coded data unit, now enlarged by several bits, travels over the link to the receiver. The receiver puts the entire stream through a checking function, if the received bit stream passes the checking criteria the data portion of the data unit is accepted and the redundant bits are discarded.



Three types of redundancy checks are common in data communications: Parity check, Cyclic Redundancy Check (CRC), and Checksum.

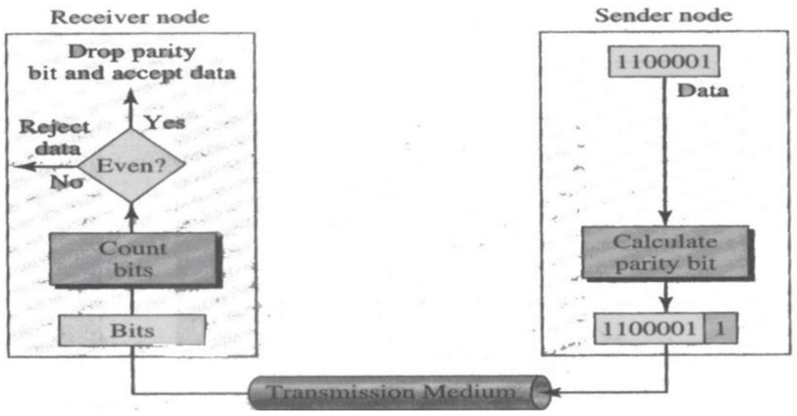


1. PARITY CHECK

The most common and least expensive mechanism for error detection is the parity check. Parity checking can be simple or two dimensional.

Simple Parity Check

In this technique, a redundant bit, called a parity bit, unit so that the total number of Is in the unit (including the parity bit) becomes even (or odd). Suppose we want to transmit the binary data unit 1100001 [ASII a (97)];



Adding the number of 1s gives us 3 an odd number. Before transmitting we pass the data unit through a parity generator. The parity generator counts the 1's and appends the parity bit (a 1 in this case end. The total number of is now 4 an even number. The system now transmits the entire expanded unit across the network link. When it reaches its destination, the receiver puts all 8 bits through an even-parity checking function. If the receiver sees 11000011, it counts four is, an even number, and the data unit passes. But if the data unit has been damaged in transit, means instead of 11000011, the receiver sees 11001011. Then when the parity checker counts the 1s, it gets 5, an odd number. The receiver knows that an error has been introduced into the data somewhere and therefore rejects the whole unit.

Some systems may use odd-parity checking, where the number of Is should be odd. The principle is the same.

Example: Suppose the sender wants to send the word world. In ASCII, the five characters are coded as

1110111	1101111	1110010	1101100	1100100
w	o	r	1	d

Each of the first four characters has an even number of is, so the parity bit is a 0. The last character (d), however, has three 1s (an odd number), so the parity bit is a 1 to make the total number of 1s even. The following shows the actual bits sent (the parity bits are underlined).

1110111<u>0</u> 1101111<u>0</u> 1110010<u>0</u> 1101100<u>0</u> 1100100<u>1</u>

Now suppose the word *world* is received by the receiver without being corrupted in transmission as 11101110 11011110 11100100 11011000 11001001, The receiver counts the is in each character and comes up with even numbers (6, 6, 4, 4, 4). The data are accepted.

If the word *world* in is corrupted during transmission and receiver get the data stream as,

111**1**1110 11011110 1110**1**100 11011000 11001001

The receiver counts the Is in each character and comes up with even and odd numbers (7, 6, 5, 4, 4). The receiver knows that the data are corrupted, discards them, and asks for retransmission.

Performance

Simple parity check can detect all single bit error It can also detect burst errors as long as the total number of bits change to odd (1, 3, 5, etc.). Let’s say we have an even-parity data unit where the total number of 1s, including the parity bit, is 6: 1000111011. If any 3 bits change value, the resulting parity will be odd and the error will be detected: 1**1**1**1**111011:9, 0110111011:7, 1**l**00**0**1**0**011:5 a11 odd. The checker would return a result of 1, and the data unit would be rejected. The same holds true for any odd number of errors.

Suppose, however, that 2 bits of the data unit are changed: 1**11**0111011:8, 1**1**00**0**11011:6, 1000**0**1101**0**:4. In each case the number of is in the data unit is still even. The parity checker will add them and return an even number although the data unit contains two errors. This method cannot detect errors where the total number of bits changed is even. If any two bits change in transmission, the changes cancel each other and the data unit will pass a parity check even though the data unit is damaged. The same holds true for any even number of errors.

Two Dimensional Parity Check

A better approach is the two dimensional parity check. In this method, block of bits is organized as a table (rows and columns). First we calculate the parity bit for each data unit. Then we organize them into a table format.

For example, shown in Figure 1.6, we have four data units shown in four rows and eight columns. We then calculate parity bit for each column and create a new row of 8 bit; they are the parity bits for the whole block. Note that the first parity bit in the fifth row is calculated based on all first bits; the second parity bit is calculated based on all second bits; and so on. We then attach the parity bits to the original data and send them to the receiver.

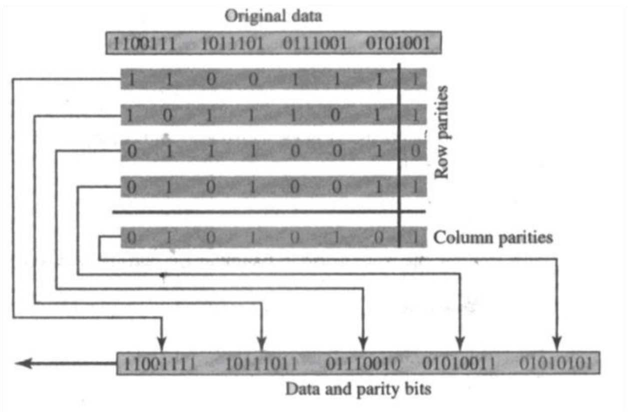


Figure 1.6 Two Dimensional Parity check

Performance

Two-dimensional parity check increases the likelihood of detecting burst errors. A redundancy of *n* bits can easily detect a burst error of n bits. A burst error of more than n bits is also detected by this method with a very high probability. There is, however, one pattern of errors that remains elusive. If 2 bits in one data unit are damaged and two bits in exactly the same positions in another data unit are also damaged, the checker will not detect an error.

2. CYCLIC REDUNDANCY CHECK (CRC)

The most powerful of the redundancy checking techniques is the cyclic redundancy check (CRC). Unlike the parity check which is based on addition, CRC is based on binary division. In CRC, instead of adding bits to achieve a desired parity, a sequence of redundant bits, called the CRC or the CRC remainder, is appended to the end of a data unit so that the resulting data unit becomes exactly divisible by a second, predetermined binary number. At its destination, the incoming data unit is divided by the same number. If at this step there is no remainder the data unit is assumed to be intact and is therefore accepted. A remainder indicates that the data unit has been damaged in transmit therefore must be rejected.

The redundancy bits used by CRC are derived by dividing the data unit by a pre determined divisor; the remainder is the CRC.

To be valid, a CRC must have two qualities; it must have exactly one less bit than the divisor, and appending it to the end of the data string must make the resulting bit sequence exactly divisible by the divisor.

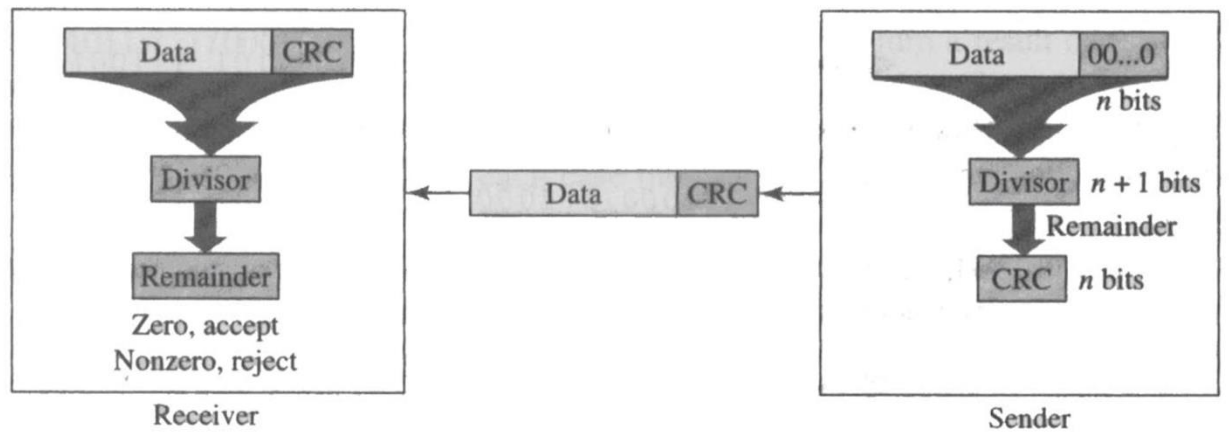


Figure 2.7 CRC generator and checker

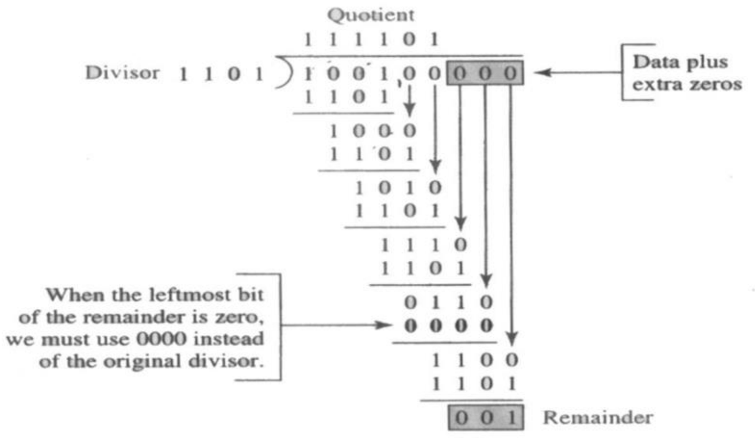
Figure 2.7 provides an outline of the three basic steps in CRC.

1. A string of *n* 0s is appended to the data unit. The number *n* is 1 less than the number of bits in the predetermined divisor, which is *n + 1* bit.
2. The newly elongated data unit is divided by the divisor, using a process called binary division. The remainder resulting from this division is the CRC.
3. The CRC of n bits derived in step 2 replaces the appended 0s at the end of the data unit. Note that the CRC may consist of all 0s.

The data unit arrives at the receiver data first, followed by the CRC. The receiver treats the whole string as a unit and divides it by the same divisor that was used to find the CRC remainder.

If the string arrives without error, the CRC checker yields a remainder of zero and the data unit passes. If the string has been changed in transit, the division yields a nonzero remainder and the data unit does not pass.

The CRC Generator



A CRC generator uses modulo-2 division. Above figure shows this process. In the first step, the 4-bit divisor is subtracted from the first 4 bits of the dividend. Each bit of the divisor is subtracted from the corresponding bit of the dividend without disturbing the next-higher bit. In our example, the divisor, 1101, is subtracted from the first 4 bits of the dividend, 1001, yielding 100 (the leading 0 of the remainder is dropped). The next unused bit from the dividend is then pulled down to make the number of bits in the remainder equal to the number of bits in the divisor. The next step, therefore, is 1000 — 1101, which yields 101, and so on.

In this process, the divisor always begins with a 1; the divisor is subtracted from a portion of the previous that is equal to it in length; the divisor can only be subtracted from a dividend/remainder whose leftmost bit is 1. Anytime the leftmost bit of the dividend/remainder is 0, a string of 0s, of the same length as the divisor, replaces the divisor in that step of the process. For example, if the divisor is 4 bits long, it is replaced by four 0s. (Remember, we are dealing with bit patterns not with quantitative values; 0000 is not the same as 0.) This restriction means that, at any step, the leftmost subtraction will be either 0 - 0 or 1 - 1, both of which equal 0. So, after subtraction, the leftmost bit of the remainder will always be a leading zero, which is dropped, and the next unused bit of the dividend is pulled down to fill out the remainder. Note that only the first bit of the remainder is dropped—if the second bit is also 0, it is retained, and the dividend/remainder for the next step will begin with 0. This process repeats until the entire dividend has been used.

The CRC Checker

A CRC checker functions exactly as the generator does. After receiving the data appended with the CRC, it does the same modulo-2 division. If the remainder is all 0s, the CRC is dropped and the data are accepted; otherwise, the received stream of bits is discarded and data are resent.

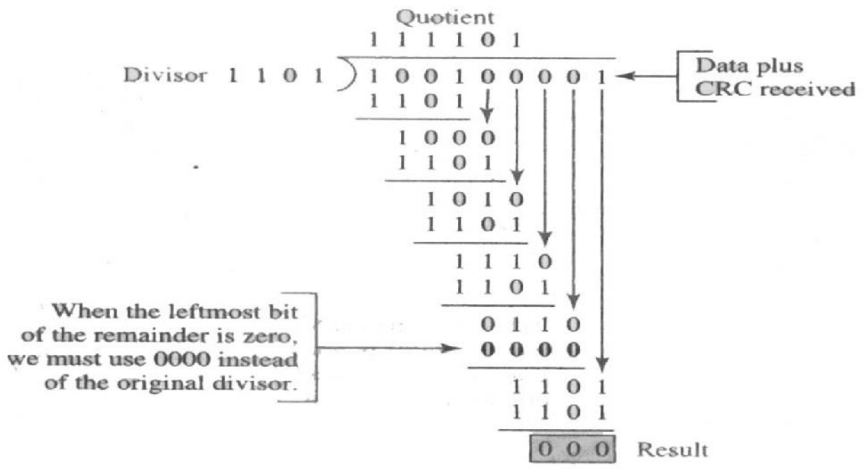


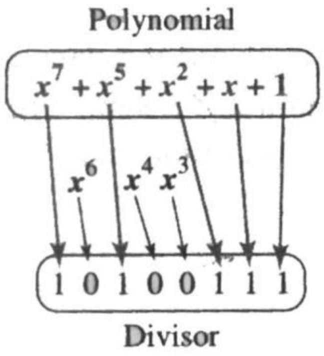
Figure above shows the same process of division in the receiver. We assume that there is no error. The remainder is therefore all 0s, and the data are accepted.

Polynomials

The divisor in the CRC generator is most often represented *not as a string* of 1s and 0s, but as an algebraic polynomial, like $\mathbf{x^7+x^5+x^2+x+1}$

The polynomial format is useful for two reasons: It is short, and it can be used to prove the concept mathematically.

The relationship of a polynomial to its corresponding binary representation is shown below.



A polynomial should be selected to have at least the following properties:

1. It should not be divisible by x.
2. It should be divisible by x + 1.

The first condition guarantees that all burst errors of a length equal to the degree of the polynomial are detected. The second condition guarantees that all burst errors affecting an odd number of bits are detected.

Example: It is obvious that we cannot choose x (binary 10) or x2 + x (binary 110) as the polynomial because both are divisible by x. However, we can choose x + 1 (binary 11) because it is not divisible by x, but is divisible by x + 1. We can also choose x + 1 (binary 101) because it is divisible by x + I (binary division).

Standard Polynomials

Some standard polynomials used by popular protocols for CRC generation are given below.

CRC-8 for ATM: $x^8 + x^2 + x + 1$

CRC-12: $x^{12} + x^{11} + x^3 + x + 1$

CRC-16: $x^{16} + x^{15} + x^2 + 1$

CRC-CCITT: $x^{16} + x^{15} + x^5 + 1$

CRC-32 used in IEEE 802:

$$x^{32} + x^{26} + x^{23} + x^{22} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x + 1$$

Performance

CRC is a very effective error detection method. If the divisor is chosen according to the previously mentioned rules,

1. CRC can detect all burst errors that affect an odd number of bits.
2. CRC can detect all burst errors of length less than or equal to the degree of the polynomial.
3. CRC can detect, with a very high probability, burst errors of length greater than the degree of the polynomial.

Example The CRC- 12 ($x^{12} + x^{11} + x^3 + x + 1$), which has a degree of 12, will detect all burst errors affecting an odd number of bits, will detect all burst errors with a length less than or equal to 12, and will detect, 99.97 percent of the time, burst errors with a length of 12 or more.

3. CHECKSUM

The third error detection method we discuss here is called the checksum. Like the parity checks and CRC, the checksum is based on the concept of redundancy.

Checksum Generator

In the sender, the checksum generator did the following actions.

1. The unit is subdivided into *k* sections, each of *n* bits.
2. All these *k* sections are added using ones complement arithmetic in such a way that the total is also *n* bits long.
3. The sum is complemented and appended to the end of the original data unit as redundancy bits, called the checksum field
4. The extended data unit is transmitted across the network. So, if the sum of the data segment is T, the checksum will be -T.

Checksum Checker

The receiver follows these steps

1. The unit is divided into k sections, each of n bits as the checksum generation.
2. All sections are added using ones complement to get the sum.
3. The sum is complemented.
4. If the result is zero, the data are accepted: otherwise, they are rejected.

Example: Suppose the following block of 16 bits is to be sent using a checksum of 8

bits. 10101001 00111001

The numbers are added using ones complement arithmetic

```
                    10101001
                    00111001
                   ----------
        Sum         11100010
        Checksum    00011101
```

```
The pattern sent is: 10101001 00111001 00011101
                        Data              Checksum
```

Performance

The checksum detects all errors involving an odd number of bits as well as most errors involving an even number of bits. However, if one or more bits of a segment are damaged and the corresponding bit or opposite value in a second segment are also damaged, the sums of those columns will not change and the receiver will not detect a problem. If the last digit of one segment is a 0 and it gets changed to a 1 in transit, then the last 1 in another segment must be changed to a 0 if the error is to go undetected.

In two-dimensional parity check, two 0s could both change to is without altering the parity because carries were discarded. Checksum retains all carries; so although two Os becoming is would not alter the value of their own column, it would change the value of the next-higher column. But anytime a bit inversion is balanced by an opposite bit inversion in the corresponding digit of another data segment, the error is invisible.

FLOW AND ERROR CONTROL

Flow and error control are the main functions of the data link layer. Let us informally define each.

Flow Control

Flow control refers to a set of procedures used to restrict the amount of data that the sender can send before waiting for acknowledgment. Flow control coordinates the amount of data that can be sent before receiving acknowledgment and is one of the most important duties of the data link layer. The flow of data must not be allowed to overwhelm the receiver.

Any receiving device has a limited speed at which it can process incoming data and a limited amount of memory in which to store incoming data. The receiving device must be able to inform the sending device before those limits are reached and to request that the transmitting device send fewer frames or stop temporarily. Incoming data must be checked and processed before they can be used. The rate of such processing is often slower than the rate of transmission. For this reason, each receiving device has a block of memory, called a buffer, reserved for storing incoming data until they are processed. If the buffer begins to fill up, the receiver must be able to tell the sender to halt transmission until it is once again able to receive.

Error Control

Error control is both error detection and error correction. It allows the receiver to inform the sender of any frames lost or damaged in transmission and coordinates the retransmission of those frames by the sender. In the data link layer, the term error control refers primarily to methods of error detection and retransmission. Error control in the data link layer is often implemented simply: Anytime an error is detected in an exchange, specified frames are retransmitted. This process is called ***automatic repeat request*** (**ARQ**).

FLOW AND ERROR CONTROL MECHANISMS

Three common flow and error control mechanisms are,

1. Stop- and-Wait ARQ,
2. Go-Back-N ARQ
3. Selective-Repeat ARQ.

These are sometimes referred to as ***sliding window protocols***.

1. STOP-AND-WAIT ARQ

Stop-and-Wait ARQ is the simplest flow and error control mechanism. It has the following features:

- The sending device keeps a copy of the last frame transmitted until it receives an acknowledgment for that frame. Keeping a copy allows the sender to retransmit lost or damaged frames until they are received correctly.
- For identification purposes, both data frames and acknowledgment (ACK) frames are numbered alternately 0 and 1. A data 0 frame is acknowledged by an ACK 1 frame, indicating that the receiver has received data frame 0 and is now expecting data frame 1. This numbering allows for identification of data frames in case of duplicate transmission (important in the case of lost acknowledgment or delayed acknowledgment).
- A damaged or lost frame is treated in the same manner by the receiver. If the receiver detects an error in the received frame, it simply discards the frame and sends no acknowledgment. If the receiver receives a frame that is out of order (0 instead of 1 or 1 instead of 0), it knows that a frame is lost. It discards the out-of-order received frame.
- The sender has a control variable, which we call S, that holds the number of the recently sent frame (0 or 1). The receiver has a control variable, which we call R, that holds the number of the next frame expected (0 or 1).
- The sender starts a timer when it sends a frame. If an acknowledgment is not received within an allotted time period, the sender assumes that the frame was lost or damaged and resends it.
- The receiver sends only positive acknowledgment for frames received safe and Sound; it is silent about the frames damaged or lost. The acknowledgment number always defines the number of the next expected frame. If frame 0 is received, ACK I is sent; if frame 1 is received, ACK 0 is sent.

Operation

In the transmission of a frame, we can have four situations: *normal operation*, the *frame is lost*, *the acknowledgement is lost,* or *the acknowledgment is delayed*.

Normal Operation

In a normal transmission, the sender sends frame 0 and waits to receive ACK 1. When ACK 1 is received, it sends frame 1 and then waits to receive ACK 0, and so on. The ACK must be received before the timer set for each frame expires. Figure below shows successful frame transmissions

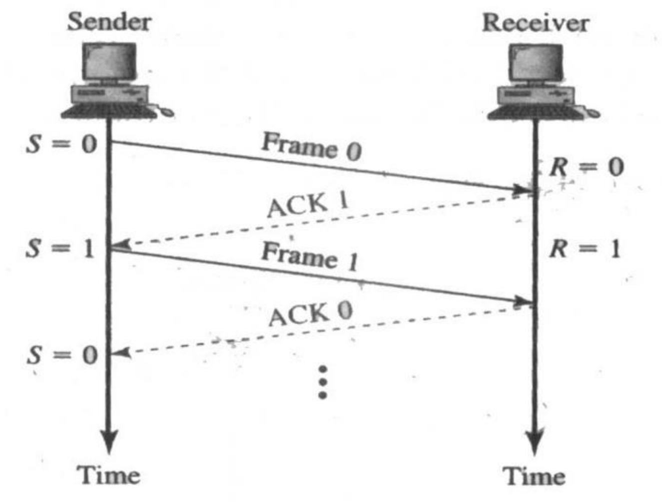


Figure: Stop and Wait ARQ, Normal operation

Lost or Damaged Frame

A lost or damaged frame is handled in the same way by the receiver; when the receiver receives a damaged frame, it discards it, which essentially means the frame is lost. The receiver remains silent about a lost frame and keeps its value of R. For example, in Figure below, the sender transmits frame 1, but it is lost. The receiver does nothing, retaining the value of R (1). After the timer at the sender site expires, another copy of frame 1 is sent.

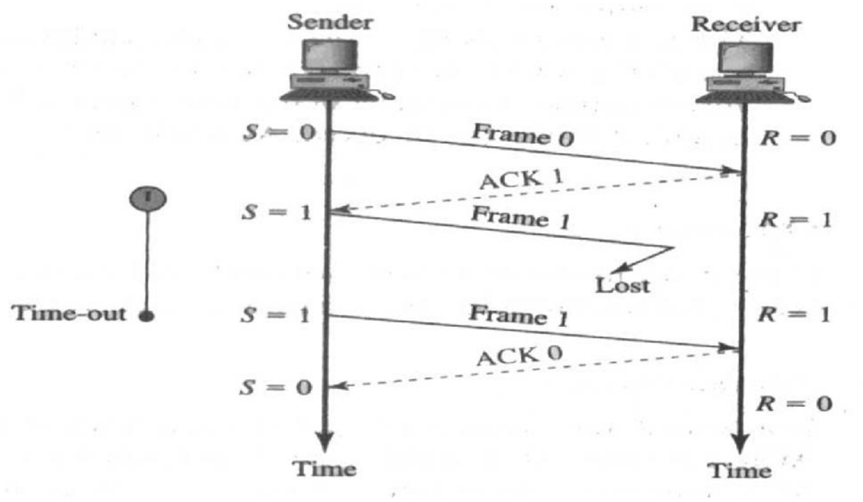


Figure: Stop and Wait ARQ, Lost or Damaged Frame

A lost or damaged acknowledgment

A lost or damaged acknowledgment is handled in the same way by the sender; if the sender receives a damaged acknowledgment, it discards it. Figure below shows a lost ACK 0. The waiting sender does not know if frame I has been received. When the timer for frame 1 expires, the sender retransmits frame 1. Note that the receiver has already received frame 1 and is expecting to receive frame 0 (R = 0). Therefore, it silently discards the second copy of frame 1.

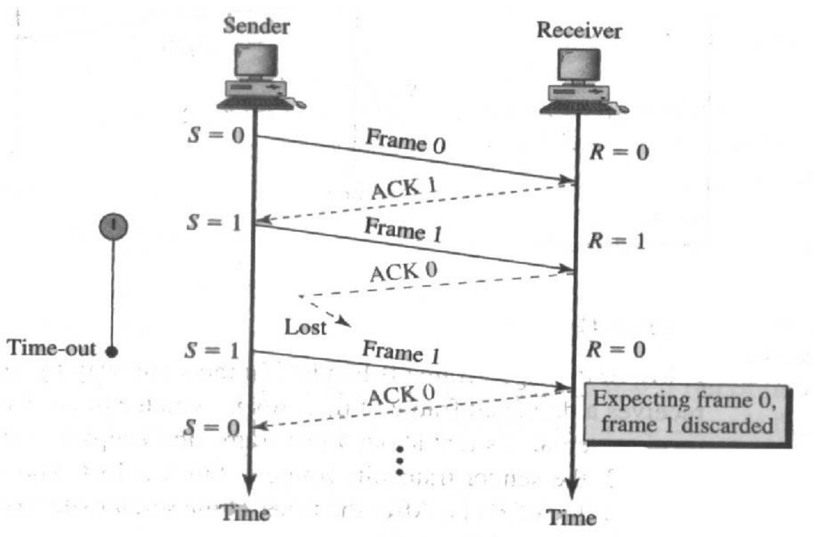


Figure: Stop and Wa1t ARQ, lost ACK frame

Delayed acknowledgment

Another problem that may occur is delayed acknowledgment. An acknowledgment can be delayed at the receiver or by some problem with the link. Figure 4 shows the delay of ACK 1; it is received after the timer for frame 0 has already expired. The sender has already retransmitted a copy of frame 0. However, the value of R at the receiver site is still 1, which means that the receiver expects to see frame 1. The receiver, therefore, discards the duplicate frame 0.

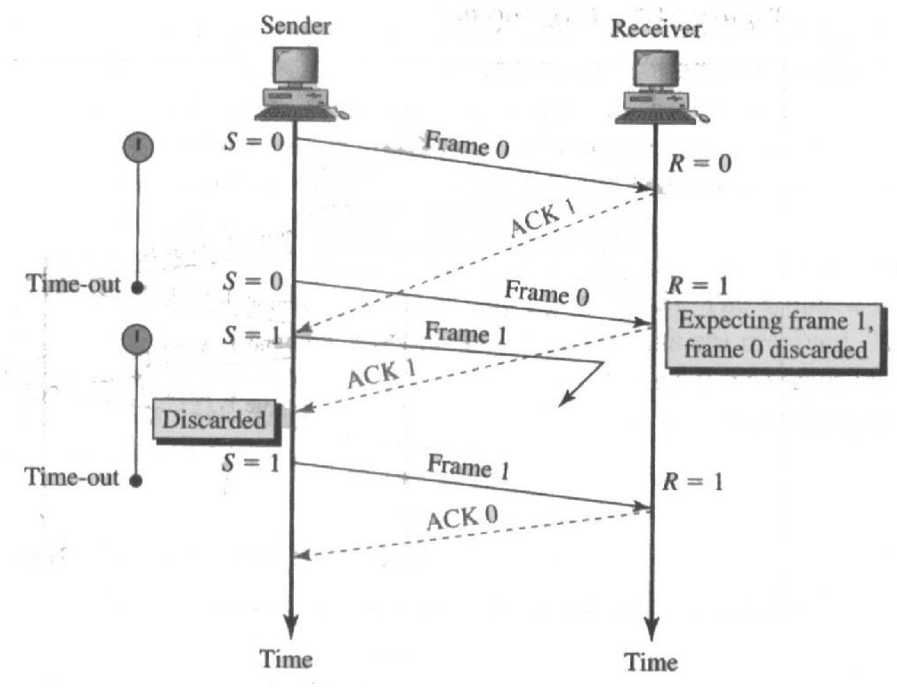


Figure 4: Stop and Wa1t ARQ, delayed ACK frame

The sender has now received two ACKs, one that was delayed and one that was sent after the duplicate frame 0 arrived. The second ACK 1 is discarded.

After the delayed ACK 1 reaches the sender, frame I is sent. However, frame 1 is lost and never reaches the receiver. The sender then receives an ACK 1 for the duplicate frame sent. If the ACKs were not numbered, the sender would interpret the second ACK as the acknowledgment for frame 1. Numbering the ACKs provides a method to keep track of the received data frames.

Bidirectional Transmission

If the two parties have two separate channels for full- duplex transmission or share the same channel for half-duplex transmission. In this case, each party needs both S and R variables to track frames sent and expected.

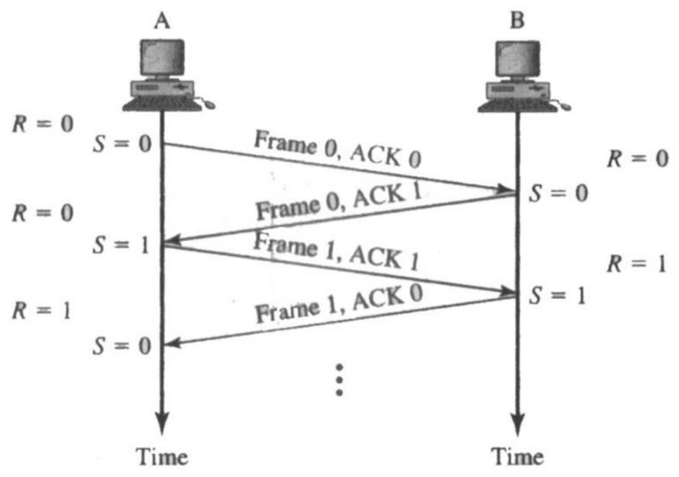


Figure 5: Bidirectional Transmission, Piggybacking

Piggybacking

Piggybacking is a method to combine a data frame with an acknowledgment. For example, in Figure 5, Stations A and B both have data to send. Instead of sending separate data and ACK frames, station A sends a data frame that includes an ACK. Station B behaves in a similar manner.

Piggybacking can save bandwidth because the overhead from a data frame and an ACK frame (addressees, CRC, etc.,) can be combined into just one frame.

2. GO-BACK-N ARQ

In Stop-and-Wait ARQ, at any point in time for a sender, there is only one frame, the outstanding frame, that is sent and waiting to be acknowledged. This is not a good use of the transmission medium. To improve the efficiency, multiple frames should be in transition while waiting for acknowledgment. In other words, we need to let more than one frame be outstanding. Two protocols use this concept: Go-Back-N ARQ and Selective Repeat ARQ.

In Go-Back-N ARQ, we can send up to W frames before worrying about acknowledgments; we keep a copy of these frames until the acknowledgments arrive. This procedure requires additional features to be added to Stop-and-Wait ARQ.

Sequence Numbers

Frames from a sending station are numbered sequentially. However, because we need to include the sequence number of each frame in the header, we need to set a limit. If the header of the frame allows m bits for the sequence number, the sequence numbers range from 0 to 2^m-1. For example, if m is 3, the only sequence numbers are 0 through 7 inclusive. However, we can repeat the sequence. So the sequence numbers are

0,l,2,3,4,5,6,7, 0,l,2,3,4,5,6,7….1

Sender Sliding Window

At the sender site, to hold the outstanding frames until they are acknowledged, we use the concept of a window. We imagine that all frames are stored in a buffer. The outstanding frames are enclosed in a window. The frames to the left of the window are those that have already been acknowledged and can be purged; those to the right of the Window cannot be sent until the window slides over them. The size of the window is at most $2^m — 1$.

The size of the window in this protocol is fixed, although we can have a variable- size window in other protocols such as TCP. The window slides to include new unsent frames when the correct acknowledgments are received. The Window is a sliding window. For example, in Figure 6a, frames 0 through 6 have been sent. In part b, the window slides two frames over because an acknowledgment was received for frames 0 and 1.

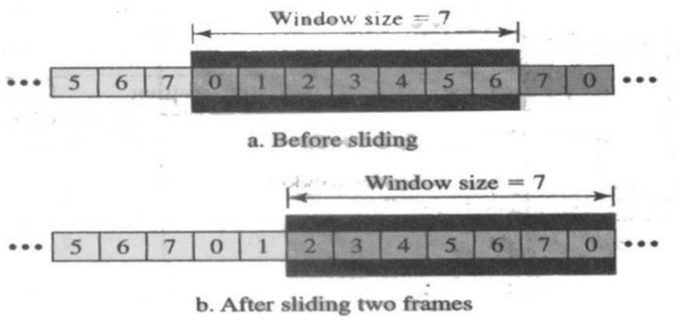


Figure 6: Sender Sliding Window

Receiver Sliding Window

The size of the window at the receiver side in this protocol is always 1. The receiver is always looking for a specific frame to arrive in a specific order. Any frame arriving out of order is discarded and needs to be resent. The receiver window also slides as shown in Figure 7. In part *a* the receiver is waiting for frame 0. When that arrives, the window slides over.

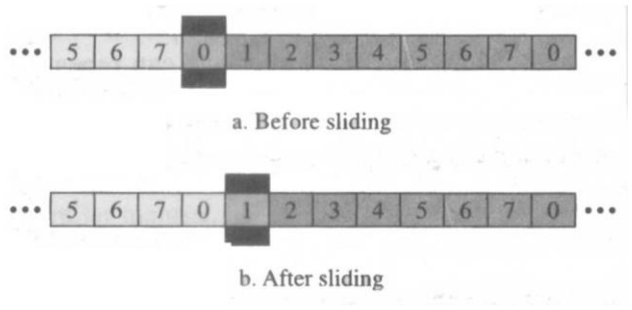


Figure 6: Sender Sliding Window

Control variables

The sender has three variables, S, S_F, and S_L. The S variable holds the sequence number of the recently sent frame; S_F holds the sequence number of the first frame in the window; and S_L holds the sequence number of the last frame in the window. The size of the window is W, where $W= S_L — S_F+ 1$.

The receiver only has one variable, R that holds the sequence number of the frame it expects to receive. If the sequence number of the received frame is the same as the value of R, the frame is accepted; if not, it is rejected. Figure 8 shows the sender and receiver window with their control variables.

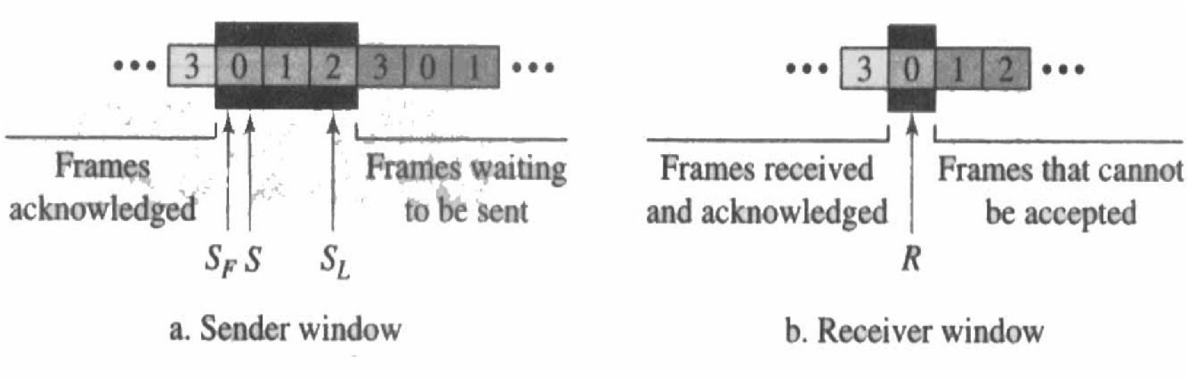


Figure 8, Control variables

Timers

The sender sets a timer for each frame sent. The receiver has no timers.

Acknowledgment

The receiver sends positive acknowledgments if a frame has arrived safe and sound and in order. If a frame is damaged or is received out of order, the receiver is silent and will discard all subsequent frames until it receives the one it is expecting. The silence of the receiver causes the timer of the unacknowledged frame to expire. This, in turn, causes the sender to go back and resend all frames, beginning with the one with the expired timer. The receiver does not have to acknowledge each frame received. It can send one cumulative acknowledgment for several frames.

Resending Frame

When a frame is damaged, the sender goes back and sends a set of frames starting from the damaged one up to the last one sent. For example, suppose the sender has already sent frame 6, but the timer for frame 3 expires. This means that frame 3 has not been acknowledged, so the sender goes back and sends frames 3, 4, 5, 6 again. That is why the protocol is called Go-Back-N ARQ.

OPERATION

Normal Operation

Figure 9 shows a normal operation of Go-Back-N ARQ. The sender keeps track of the outstanding frames and updates the variables and windows as the acknowledgments arrive.

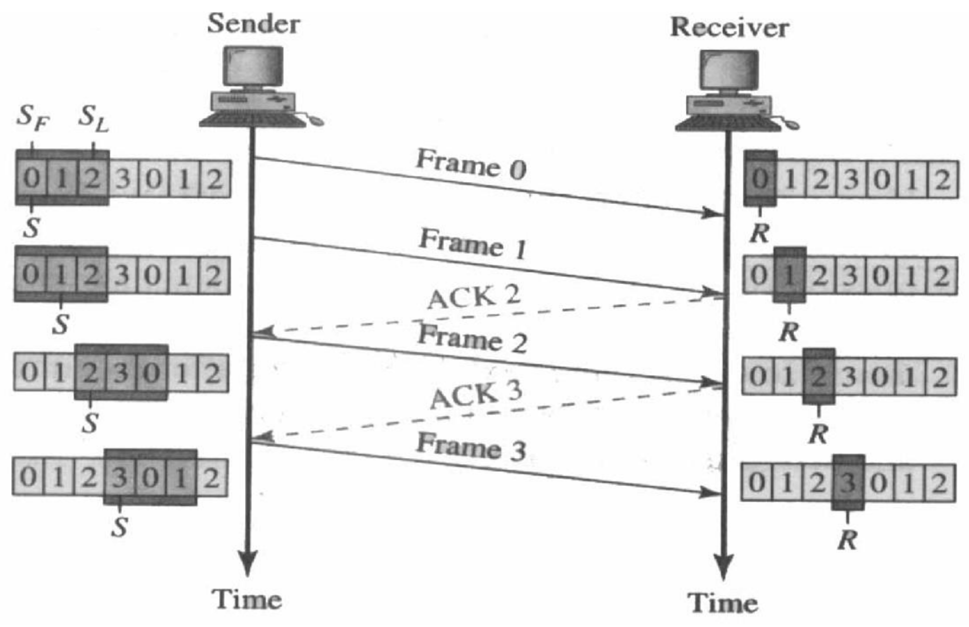


Figure 9 Go-Back-N ARQ, normal operation

Damaged or Lost Frame

Figure 10 shows, the situation when a frame is lost. It shows that frame 2 is lost. Note that when the receiver receives frame 3, it is discarded because the receiver is expecting frame 2, not frame 3 (according to its window). After the timer for frame 2 expires at the sender site, the sender sends frames 2 and 3 (it goes back to 2).

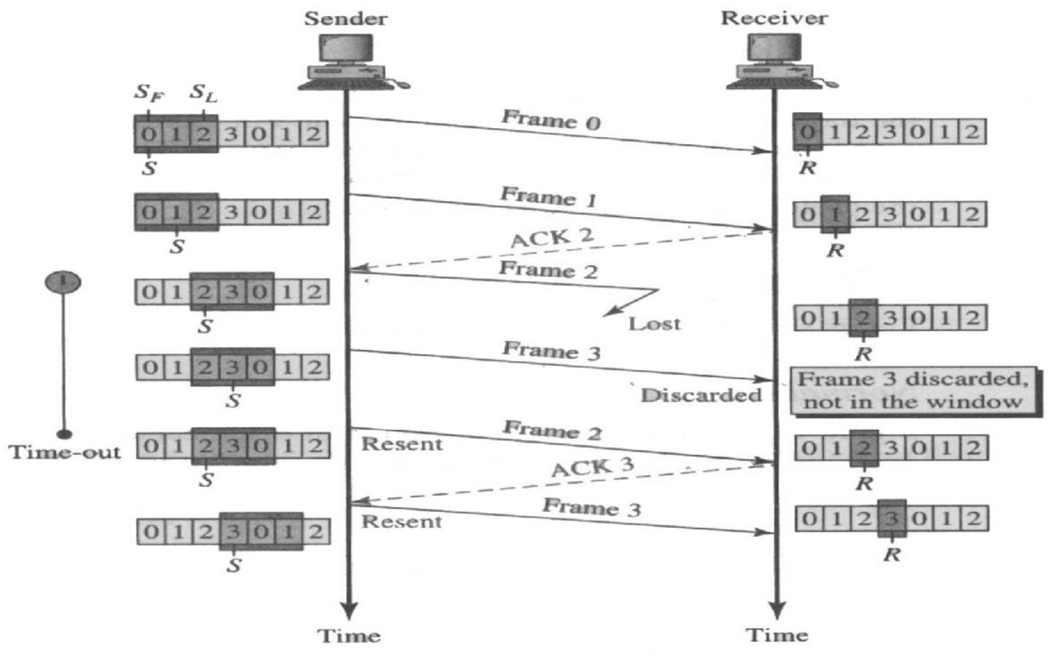


Figure 10: Damaged or Lost Frame

Damaged or lost Acknowledgment

If an acknowledgment is damaged or lost, we can have two situations. If the next acknowledgment arrives before the expiration of any timer, there is no need for retransmission of frames because acknowledgments are cumulative in this protocol. ACK 4 means ACK 1 to ACK 4. So if ACK 1, ACK 2, and ACK 3 are lost, ACK 4 covers them. However, if the next ACK arrives after the time-out, the frame and all the frames after that are resent. The receiver never resends an ACK.

Delayed Acknowledgment

A delayed acknowledgment triggers the resending of frames.

Sender Window Size

We can now show why the size of the sender window must be less than 2^m. As an example, we choose m = 2, which means the size of the window can be 2^m — 1, or 3. Figure 11 compares a window size of 3 and 4.

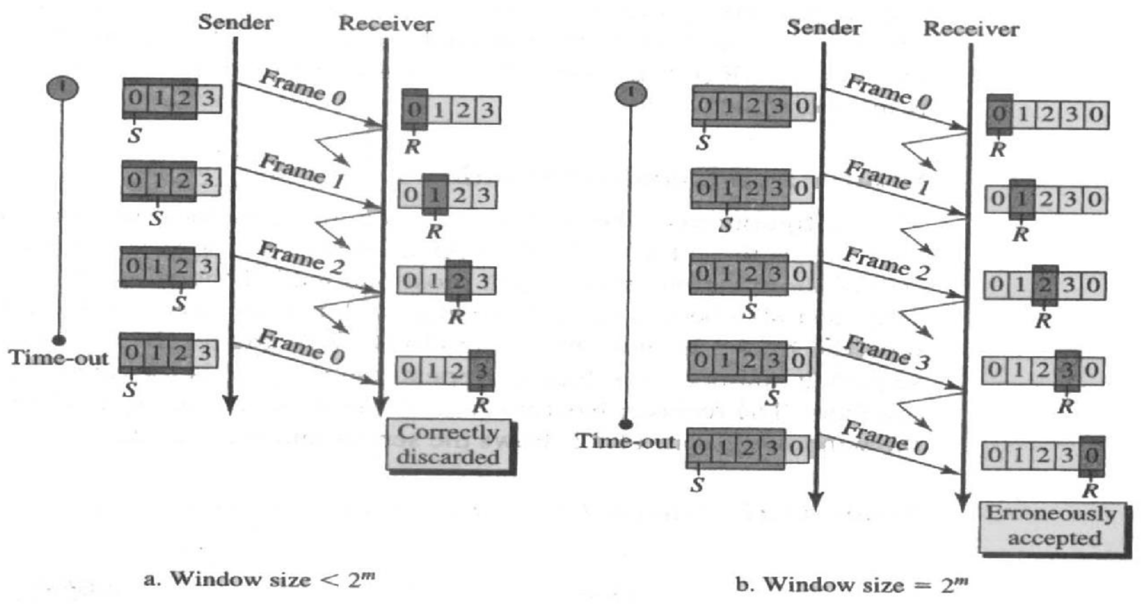


Figure 11 Go-Back-N ARQ: sender Window size

If the size of the window is 3 (less than 22) and all three acknowledgments are lost, the frame 0 timer expires and all three frames are resent. However, the window of the receiver is now expecting frame 3, not frame 0, so the duplicate frame is correctly discarded. On the other hand, if the size of the window is 4 (equal to 22) and all acknowledgments are lost, the sender will send the duplicate of frame 0. However, this time the window of the receiver expects to receive frame 0, so it accepts frame 0, not as a duplicate, but as the first frame in the next cycle. This is an error.

Bidirectional Transmission and Piggybacking

As in the case of Stop-and-Wait ARQ, Go-Back N ARQ can also be bidirectional We can also use piggybacking to improve the efficiency of the transmission However, each direction needs both a sender window and a receiver window.

3. SELECTIVE REPEAT ARQ

Go-Back-N ARQ simplifies the process at the receiver site. The receiver keeps3 track of only one variable, and there is no need to buffer out-of-order frames; they are simply discarded. However, this protocol is very inefficient for a noisy link. In a noisy link a frame has a higher probability of damage, which means the resending of multiple frames. This resending uses up the bandwidth and slows down the transmission. For noisy links, there is another mechanism that does not resend N frames when just one frame is damaged; only the damaged frame is resent. This mechanism is called Selective Repeat ARQ. It is more efficient for noisy links, but the processing at the receiver is more complex.

Sender and Receiver Windows

The configuration of the sender and its control variables for Selective Repeat ARQ is the same as those for Go-Back-N ARQ. But the size of the window should be at most one-half of the value $2^{m.}$ The receiver window size must also be this size. This window, however, specifies the range of the accepted received frame. In other words, in Go-Back-N, the receiver is looking for one specific sequence number; in Selective Repeat, the receiver is looking for a range of sequence numbers. The receiver has two control variables R_F and R_L to define the boundaries of the window. Figure 12 shows the sender and receiver windows.

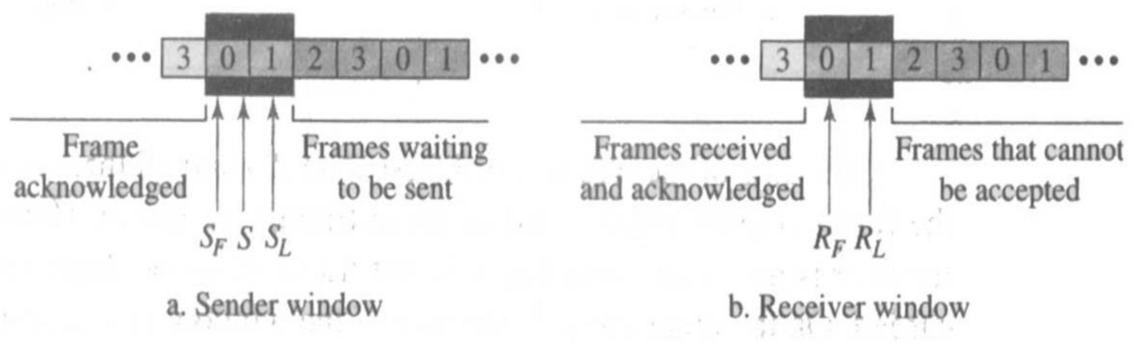


Figure 12 Selective Repeat ARQ, sender and receiver windows

Selective Repeat ARQ also defines a negative acknowledgment (NAK) that reports the sequence number of a damaged frame before the timer expires.

Operation

Figure 13 show the operation of the mechanism of Selective Repeat ARQ with an example of a lost frame.

Frames 0 and I are accepted when received because they are in the range specified by the receiver window. When frame 3 is received, it is also accepted for the same reason. However, the receiver sends a NAK 2 to show that frame 2 has not been received. When the sender receives the NAK 2, it resends only frame 2, which is then accepted because it is in the range of the window.

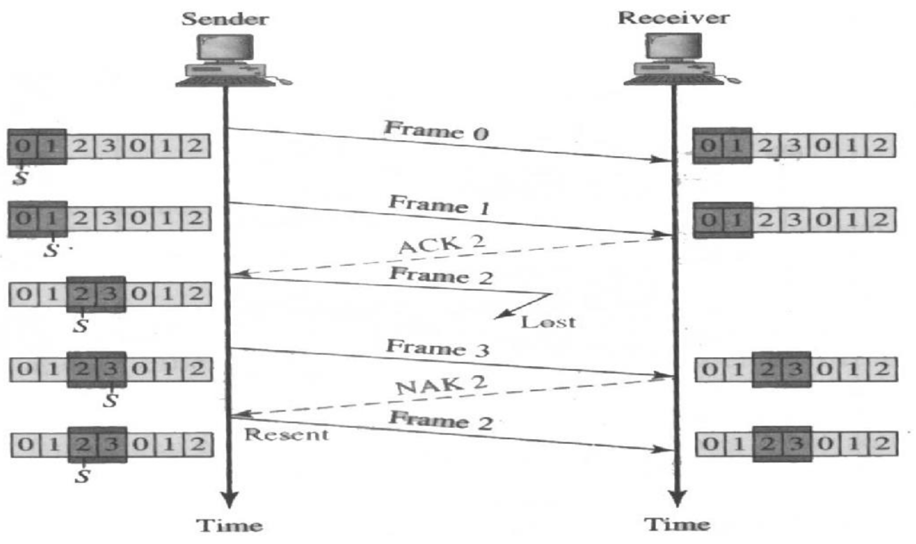


Figure 13 Selective Repeat ARQ, lost frame

Sender Window Size

We can now show why the size of the sender and receiver Windows must be at most one-half of 2^m. For an example, we choose m = 2, which means the size of the Window should be $2^m/2$ or 2. Figure 14 compares a window size of 2 with a window size of 3.

If the size of the window is 2 and all acknowledgments are lost, the timer for frame 0 expires and frame 0 is resent. However, the window of the receiver is now expecting frame 2, not frame 0, so this duplicate frame is correctly discarded. When the size of the window is 3 and all acknowledgments are lost, the sender sends a duplicate of frame 0. However, this time, the window of the receiver expects to receive frame 0 (0 is part of the Window), so it accepts frame 0, not as a duplicate, but as the first frame in the next cycle. This is clearly an error.

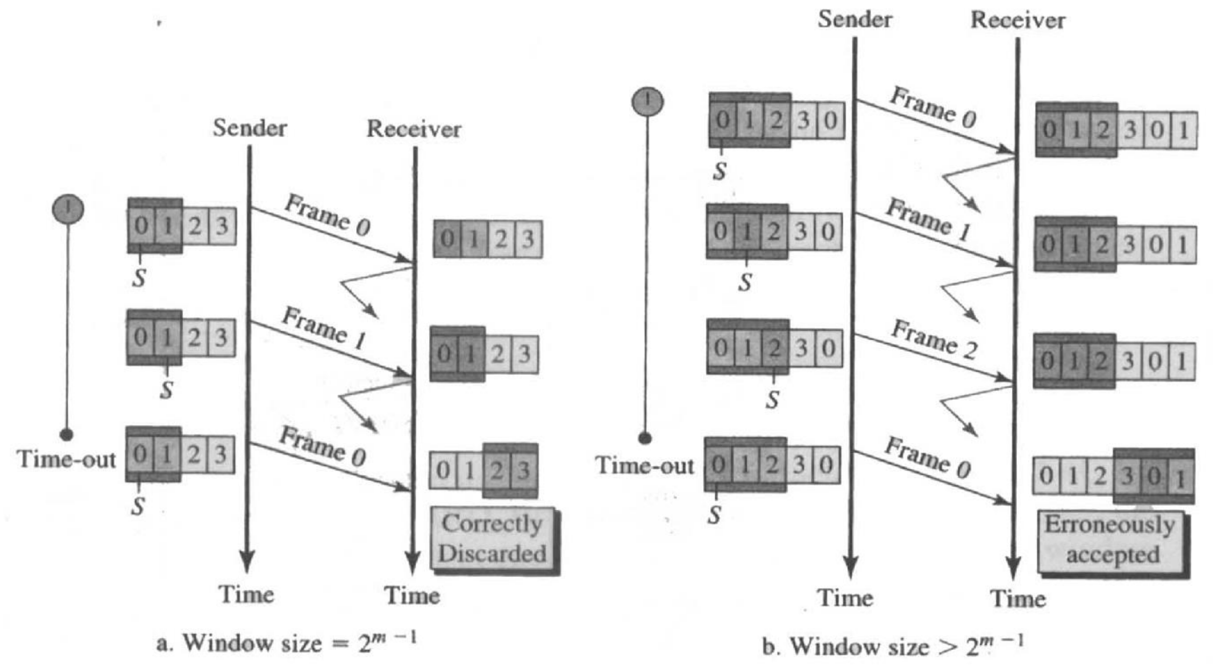


Figure 14 Selective Repeat ARQ, sender window size

Bidirectional Transmission and Piggybacking

As in the case of Stop-and-Wait ARQ and the Go-Back-N ARQ, Selective Repeat ARQ can also be bidirectional. We can use piggybacking to improve the efficiency of the transmission. However each direction needs both a sender window and a receiver window.