

which the 1-valued bit in position (2,2) is corrupted and switched to a 0—an error that is both detectable and correctable at the receiver. Although our discussion has focused on the original  $d$  bits of information, a single error in the parity bits themselves is also detectable and correctable. Two-dimensional parity can also detect (but not correct!) any combination of two errors in a packet. Other properties of the two-dimensional parity scheme are explored in the problems at the end of the chapter.

The ability of the receiver to both detect and correct errors is known as **forward error correction (FEC)**. These techniques are commonly used in audio storage and playback devices such as audio CDs. In a network setting, FEC techniques can be used by themselves, or in conjunction with link-layer ARQ techniques similar to those we examined in Chapter 3. FEC techniques are valuable because they can decrease the number of sender retransmissions required. Perhaps more important, they allow for immediate correction of errors at the receiver. This avoids having to wait for the round-trip propagation delay needed for the sender to receive a NAK packet and for the retransmitted packet to propagate back to the receiver—a potentially important advantage for real-time network applications [Rubenstein 1998] or links (such as deep-space links) with long propagation delays. Research examining the use of FEC in error-control protocols includes [Biersack 1992; Nonnenmacher 1998; Byers 1998; Shacham 1990].

## 5.2.2 Checksumming Methods

In checksumming techniques, the  $d$  bits of data in Figure 5.4 are treated as a sequence of  $k$ -bit integers. One simple checksumming method is to simply sum these  $k$ -bit integers and use the resulting sum as the error-detection bits. The **Internet checksum** is based on this approach—bytes of data are treated as 16-bit integers and summed. The 1s complement of this sum then forms the Internet checksum that is carried in the segment header. As discussed in Section 3.3, the receiver checks the checksum by taking the 1s complement of the sum of the received data (including the checksum) and checking whether the result is all 1 bits. If any of the bits are 0, an error is indicated. RFC 1071 discusses the Internet checksum algorithm and its implementation in detail. In the TCP and UDP protocols, the Internet checksum is computed over all fields (header and data fields included). In IP the checksum is computed over the IP header (since the UDP or TCP segment has its own checksum). In other protocols, for example, XTP [Strayer 1992], one checksum is computed over the header and another checksum is computed over the entire packet.

Checksumming methods require relatively little packet overhead. For example, the checksums in TCP and UDP use only 16 bits. However, they provide relatively weak protection against errors as compared with cyclic redundancy check, which is discussed below and which is often used in the link layer. A natural question at this point is, Why is checksumming used at the transport layer and cyclic redundancy