allow the receiver to sometimes, *but not always,* detect that bit errors have occurred. Even with the use of error-detection bits there still may be **undetected bit errors**; that is, the receiver may be unaware that the received information contains bit errors. As a consequence, the receiver might deliver a corrupted datagram to the network layer, or be unaware that the contents of a field in the frame's header has been corrupted. We thus want to choose an error-detection scheme that keeps the probability of such occurrences small. Generally, more sophisticated error-detection and-correction techniques (that is, those that have a smaller probability of allowing undetected bit errors) incur a larger overhead—more computation is needed to compute and transmit a larger number of error-detection and -correction bits.

Let's now examine three techniques for detecting errors in the transmitted data—parity checks (to illustrate the basic ideas behind error detection and correction), checksumming methods (which are more typically used in the transport layer), and cyclic redundancy checks (which are more typically used in the link layer in an adapter).

5.2.1 Parity Checks

Perhaps the simplest form of error detection is the use of a single **parity bit**. Suppose that the information to be sent, D in Figure 5.4, has d bits. In an even parity scheme, the sender simply includes one additional bit and chooses its value such that the total number of 1s in the $d + 1$ bits (the original information plus a parity bit) is even. For odd parity schemes, the parity bit value is chosen such that there is an odd number of 1s. Figure 5.4 illustrates an even parity scheme, with the single parity bit being stored in a separate field.

Receiver operation is also simple with a single parity bit. The receiver need only count the number of 1s in the received $d + 1$ bits. If an odd number of 1-valued bits are found with an even parity scheme, the receiver knows that at least one bit error has occurred. More precisely, it knows that some *odd* number of bit errors have occurred.

But what happens if an even number of bit errors occur? You should convince yourself that this would result in an undetected error. If the probability of bit errors is small and errors can be assumed to occur independently from one bit to the next, the probability of multiple bit errors in a packet would be extremely small.

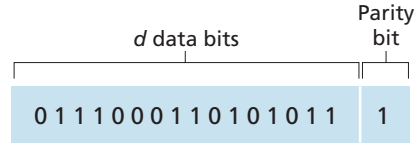

Figure 5.4 ♦ One-bit even parity

In this case, a single parity bit might suffice. However, measurements have shown that, rather than occurring independently, errors are often clustered together in "bursts." Under burst error conditions, the probability of undetected errors in a frame protected by single-bit parity can approach 50 percent [Spragins 1991]. Clearly, a more robust error-detection scheme is needed (and, fortunately, is used in practice!). But before examining error-detection schemes that are used in practice, let's consider a simple generalization of one-bit parity that will provide us with insight into error-correction techniques.

Figure 5.5 shows a two-dimensional generalization of the single-bit parity scheme. Here, the d bits in D are divided into i rows and j columns. A parity value is computed for each row and for each column. The resulting $i + j + 1$ parity bits comprise the link-layer frame's error-detection bits.

Suppose now that a single bit error occurs in the original d bits of information. With this **two-dimensional parity** scheme, the parity of both the column and the row containing the flipped bit will be in error. The receiver can thus not only *detect* the fact that a single bit error has occurred, but can use the column and row indices of the column and row with parity errors to actually identify the bit that was corrupted and *correct* that error! Figure 5.5 shows an example in

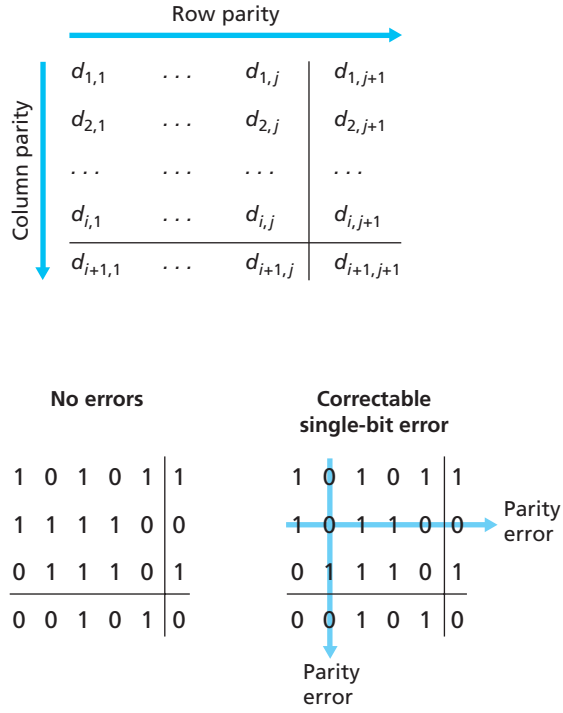

Figure 5.5 ♦ Two-dimensional even parity