

Polynomials in GF(2) and CRCs

This lecture covers arithmetic with polynomials that have coefficients from $GF(2)$. These operations are the basis of many useful telecommunications functions including computation of cyclic redundancy checks (CRCs).

After this lecture you should be able to: represent a sequence of bits as a polynomial with coefficients from $GF(2)$, compute the result of multiplying a polynomial by x^n , compute the result of dividing two polynomials, compute the value of a CRC given the message and generator polynomials, and determine if a CRC computation indicates an error has occurred.

GF(2)

A Galois field, denoted as $GF(q)$, is a set of integers and two operations that have certain properties. One of the properties is closure – the result of any operation on two elements of the field is also in the field.

For example, $GF(2)$ includes two integers (0 and 1) and the addition and multiplication operations are defined as addition and multiplication with the result taken modulo-2.

Exercise 1: Write the addition, subtraction and multiplication tables for $GF(2)$. What logic function can be used to implement modulo-2 addition? Modulo-2 multiplication?

Exercise 2: What are the possible results if we used values 0 and 1 but the regular definitions of addition and multiplication? Would this be a field?

Representing Codewords as Polynomials

Thus far we've represented codewords as sequences of bits. We can also represent codewords as polynomials with coefficients from $GF(2)$. For example, the polynomial:

$$1x^3 + 0x^2 + 1x^1 + 1x^0 = x^3 + x^1 + 1$$

can be used to represent the codeword 1011.

Exercise 3: What is the polynomial representation of the codeword 01101?

Polynomials are used to describe codes because many properties of codes can be derived from the mathematical properties of polynomials.

Note that it is the coefficients of the polynomial that are important. The polynomial itself is never evaluated and the variable x that appears in these polynomials is just a dummy variable. These polynomials can thus also be viewed as binary numbers or

bit strings where the order of each term indicates the bit position.

Polynomial Arithmetic

We can add, subtract, multiply and divide polynomials with coefficients in $GF(2)$. These operations are the basis for many useful communication-related functions including convolutional codes for FEC (Forward Error Correction), CRCs (Cyclic Redundancy Checks), and PRBS (Pseudo-Random Bit Sequence) generators.

Exercise 4: What is the result of multiplying $x^2 + 1$ by $x^3 + x$ if the coefficients are regular integers? If the coefficients are values in $GF(2)$?

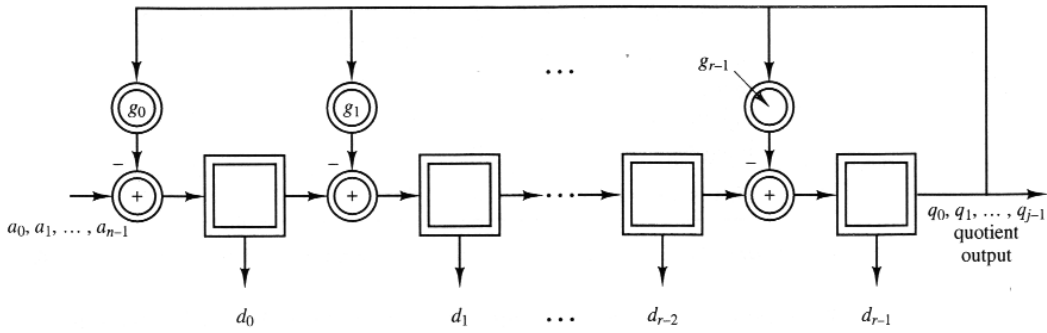
Digital Implementation of Polynomial Arithmetic

Arithmetic on polynomials with $GF(2)$ coefficients can be implemented with simple digital logic circuits. Flip-flops, organized as shift registers, store the values of the coefficients and XOR and AND gates are used to compute modulo-2 addition and multiplication. The bits corresponding to codeword(s) are input and output sequentially, bit by bit, into the polynomial arithmetic circuits.

It's simpler to do arithmetic using polynomials in $GF(2)$ than using regular integers because we do not need to compute carries when computing results.

Cyclic Redundancy Checks

A Cyclic Redundancy Check (CRC) code is used to detect errors in a sequence of k data bits. A "codeword" of n bits is transmitted for each k bits. The



length of the CRC is thus $n - k$. The algorithm used to compute the CRC is as follows:

The data to be transmitted, treated as a polynomial, is multiplied by x^{n-k} which appends $n - k$ zero bits. This new polynomial, $M(x)$, is divided by a *generator polynomial*, $G(x)$. The result is a quotient and a remainder:

$$\frac{M(x)}{G(x)} = Q(x) + R(x)$$

We then replace the last $n - k$ bits of $M(x)$ with $R(x)$. This is equivalent to adding (or subtracting) $R(x)$ from $M(x)$. This ensures that the new polynomial will be divisible by $G(x)$.

The receiver carries out the same polynomial division operation on the combination of the message bits and CRC. If the remainder is not zero then at least one of the bits must have changed and an error has been detected.

Computing the CRC

Computing the CRC requires polynomial division. The process involves repeated subtraction of the generator polynomial from the message polynomial. Unlike regular division, to compute the CRC we only need to compute the remainder.

Exercise 5: If the generator polynomial is $G(x) = x^3 + x + 1$ and the data to be protected is 1001, what are $n - k$, $M(x)$ and the CRC? Check your result. Invert the last bit of the CRC and compute the remainder again.

A circuit to perform the division of the polynomials can be implemented using a shift register (SR) that holds the result of the intermediate remainder after each subtraction. The shift register only has to hold $(n - k)$ bits.

The diagram above¹ shows a circuit that performs polynomial division. The squares represent flip-flops in the SR with the most significant bit of the intermediate remainder in the right-most bit. The circles labeled g_i represent either a connection or no connection depending on the coefficient of $G(x)$. The circles with a plus represent modulo-2 addition (or subtraction) implemented using XOR gates. The input labelled a is the message.

The SR bits are initialized to zero so that the first $n - k$ (data) bits are loaded into the SR unchanged. At each subsequent step in the division the generator polynomial (represented by the presence or absence of the connections labelled g_i) is or isn't subtracted by the xor gates from the intermediate remainder in the SR depending on the value of the most significant bit of the quotient (rightmost bit of the SR). The next input bit is also appended to the intermediate remainder. At the end of the process the shift register holds the final remainder $R(x)$ which is appended to the message as the CRC.

There are alternative CRC generator implementations that avoid the $n - k$ -bit delay associated with initializing the SR.

Checking the CRC

At the receiver the same circuit can be used to divide the received message and the appended remainder polynomial by the generator polynomial. If the remainder is zero then the received polynomial must be a multiple of the generator polynomial. This is always the case when we subtract the remainder $R(x)$ from the message polynomial. Therefore if the remainder

¹From *Error Control Systems* by S. B. Wicker.

in the SR is non-zero then there must have been an error.

CRC Error Detection Performance

The ability of the CRC to detect an error depends on the type of error.

If the errors happen in a burst then a CRC computed using a properly-chosen generator polynomial of length $n - k$ is guaranteed to detect all burst of length $n - k$ or less and will detect many longer bursts.

If the received bits are completely random then the probability of not detecting an error is the probability that a random sequence of $n - k$ bits matches the required checksum.

Exercise 6: What is the probability that a randomly-chosen set of $n - k$ parity bits will match the correct parity bits for a given codeword? Assuming random data, what is the undetected error probability for a 16-bit CRC? For a 32-bit CRC? How long a CRC is required to guarantee detection of all single-bit errors?

Standard CRC Generator Polynomials

There are several CRC generator polynomials in common use. The most common lengths are 16 and 32 bits since these are multiples of 8 bits. All(?) IEEE 802 standards use the same 32-bit CRC polynomial typically called “CRC-32”. The ITU has defined a 16-bit CRC generator polynomial (“CRC-16-CCITT”) that is also used in various standards.