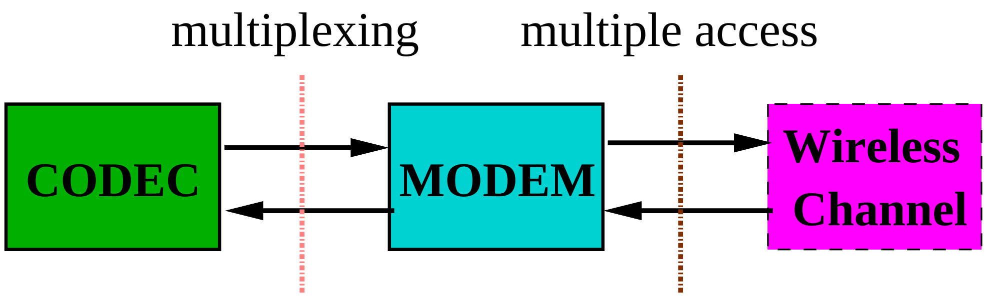
Revision of Lecture Twenty

- Previous lecture has discussed equalisation using **Viterbi algorithm**: Note similarity with channel decoding using **maximum likelihood sequence estimation** principle

- It also discusses **blind equalisation** based on **constant modulus algorithm** and **soft decision directed** method: Note low complexity of algorithm, and stochastic gradient adaptive principle

- Next a few lectures we turn to important topic of **multiple access** techniques, with briefly discussion on **channelisation spreading codes** and **CDMA** technology

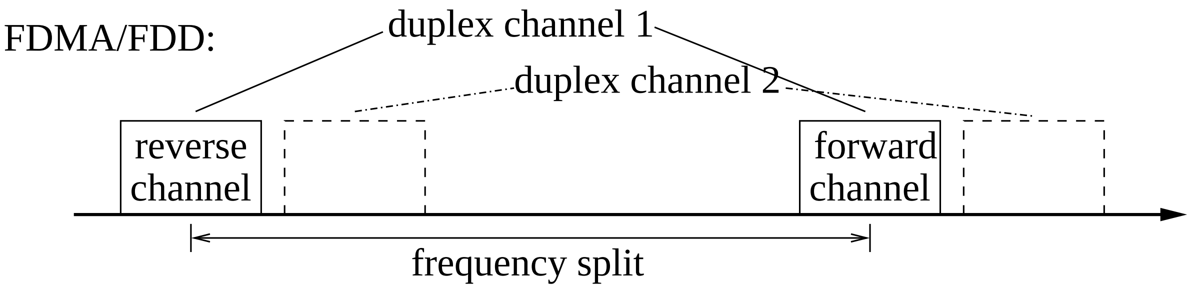


- We will also discuss **medium access control**, MAC, the important sublayer linking physical layer, PHY, and network layer, as well as higher-layer protocols

Duplexing

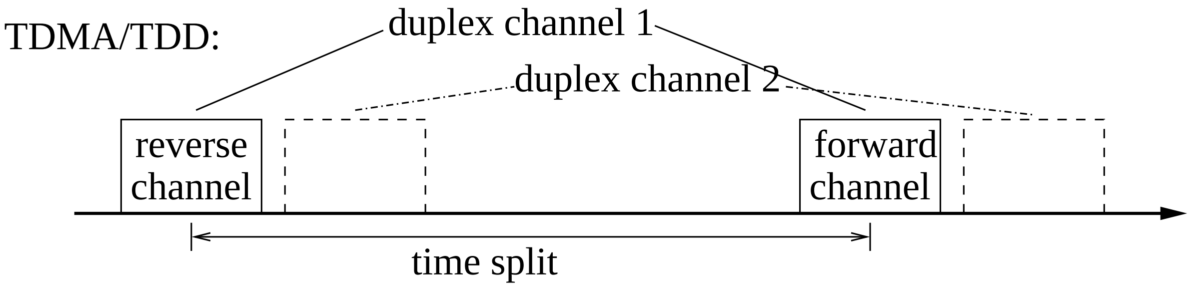
- **Duplexing**: mobile can simultaneously sent to and receive from base station. A duplexing channel consists of two simplex channels
- **Frequency division duplexing**: employ two distinct frequency bands, one for forward channel (downlink, base to mobile) and the other for reverse channel (uplink, mobile to base)

  A duplexer in transceiver switches between two frequency bands to operate as either transmitter or receiver

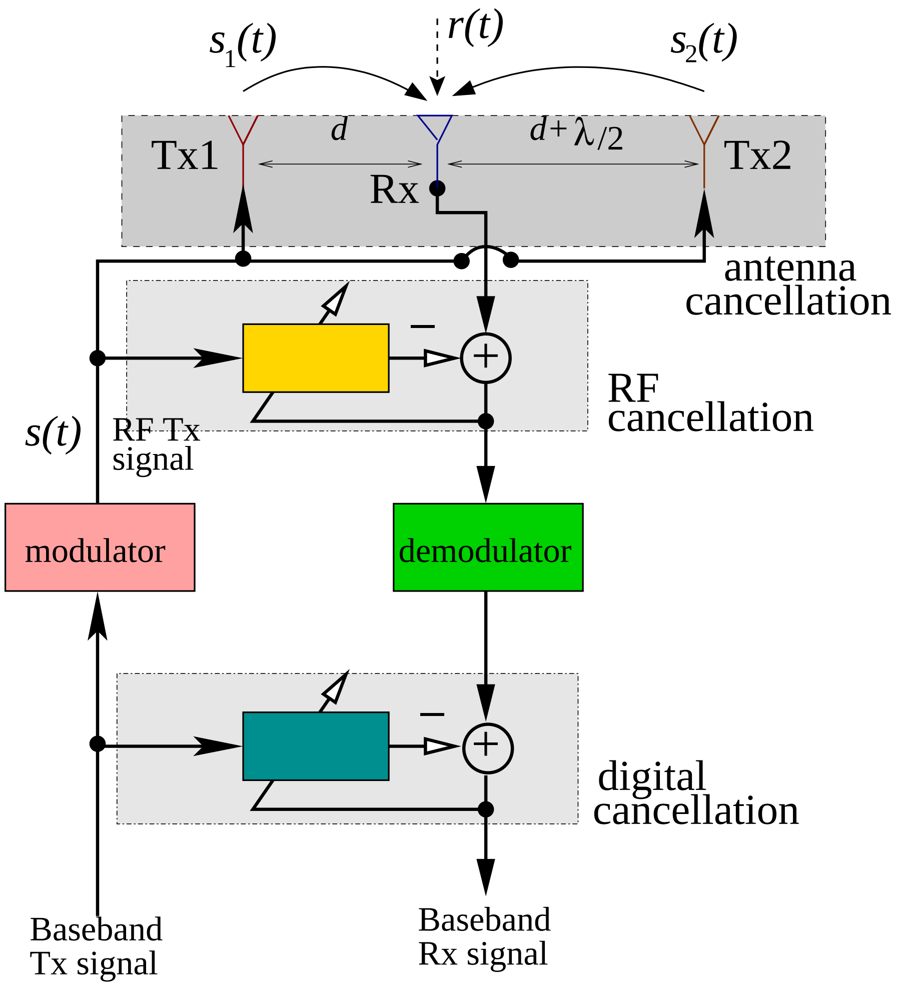
  - With FDD protocol, which dominates current wireless systems, uplink and downlink channels are different, as they are in different frequency bands
- **Time division duplexing**: employ single frequency band but use time split to provide forward and reverse slots. There is no need for a switch but time delay between forward and reverse channels may be notable

  Transceiver operates on same frequency band as either transmitter or receiver

  - With TDD protocol, however, uplink and downlink channels can be reciprocal, i.e. they are the same, as they both are in same frequency band

Space-Division Duplexing



- To achieve full duplexing, FDD and TDD protocols require two channel resources, one for transmitting, the other for receiving
- Is it possible to achieve full duplexing just using a single channel resource?
  - Problem: Strong transmit signal coming out Tx antenna will overwhelm very weak receive signal at Rx antenna
- Potential solution: "space-division duplexing", consisting three stages of "noise" cancellation
- Antenna cancellation: two Tx antennas and one Rx antenna arranged as shown in figure
  - In receive signal of $r(t) + s_1(t) + s_2(t)$
  - Tx signals $s_1(t)$ and $s_2(t)$ have approximately phase shift of 180°
  - They largely cancel out each other
- Analog cancellation: transmitted RF signal $s(t)$ is known and available, RF cancellation removes most of transmitted RF signal left in the received RF signal
- Digital cancellation: transmitted baseband signal is known and available, digital cancellation further removes most of residual transmitted baseband signal in the received baseband signal

Multiple Access Techniques

- **Multiple access**: allow many users to share simultaneously a finite amount of radio spectrum
  - In terms of network protocol architecture: medium access control which is part of data link layer

1. **Frequency division multiple access**: Total system bandwidth is divided into narrow frequency slots. Each user is allocated a unique frequency band or channel
   - A user is free to transmit or receive all the time on its allocated radio channel, but the cost of transceiver is high, as each has to be designed on a different band
2. **Time division multiple access**: Time frame is divided into slots (channels). Each user is allocated a particular time slot or channel
   - A user is limited to transmit or receive only regular bursts of a wideband signal, but it takes advantages of digital technologies
2. **Code division multiple access**: User data are spread by high-rate chip sequences to entire system bandwidth. Each user is allocated a unique code
   - Hardware requires high-rate electronics, but this technology offers much higher capacity and many advantages
4. **Space division multiple access**: If there are no separation in frequency or time or code domain, an alternative way of separating different users is spatial separation
   - For example, control radiated energy for each user in space or exploit different arrival angles using multiple antennas with spatial processing
   - SDMA utilizes user specific CIRs to distinguish/separate users

Multiple Access Techniques (continue)

- Channels are dynamically allocated and how to make reservation to gain an access may involve a contention process (we'll come to this issue in next lecture)

- FDMA and TDMA have a **hard capacity**: no more user can access after reaching the capacity

- CDMA and SDMA have **soft capacity**: they allow more users at a cost of gradual degraded quality
  - Hence, CDMA and SDMA are **interference limited**: capacity limited by MAI

- There are many combinations of multiple access/duplexing
  - GSM uses TDMA/FDD: on a radio channel, time frame is divided into 8 slots to support 8 users; and for a user, the forward and reverse channels are separated in frequency by 45 MHz
  - UMTS (UTRAN) provides both FDD and TDD
  - For FDD, downlink channel and uplink channel are generally different; for TDD, downlink channel and uplink channel may be regarded as the same
  - Implication: for TDD, base station can identify uplink channel and uses it as the estimated downlink channel in its precoding beamforming transmission to mobile

Numbers of Channels in FDMA / TDMA

- Let B_{total} be the total system bandwidth, B_{guard} be the guard band at edge, and B_{ch} the single radio channel bandwidth. Then the number of channels in a FDMA system:

$$N = \frac{B_{total} - 2B_{guard}}{B_{ch}}$$

- Give B_{total} and B_{guard}, and let m be the maximum users supported on each B_{ch}. Then the number of channels in a TDMA system:

$$N = \frac{m(B_{total} - 2B_{guard})}{B_{ch}}$$

- Let b_{OH} be the overhead bits per frame and b_{Tot} the total bits per frame. Then the efficiency of TDMA is defined by

$$\eta_f = \left(1 - \frac{b_{OH}}{b_{Tot}}\right) \times 100\%$$

- AMPS uses FDMA/FDD with $B_{total} = 12.5$ MHz, $B_{guard} = 10$ kHz and $B_{ch} = 30$ kHz

$$N = \frac{12.5 \times 10^6 - 2(10 \times 10^3)}{30 \times 10^3} = 416$$

Comparison of FDMA / TDMA (continue)

- In GSM forward link, $B_{total} = 25$ MHz, $B_{ch} = 200$ kHz and each B_{ch} supports 8 speech channels. Assuming $B_{guard} = 0$, then

$$N = \frac{8(25 \times 10^6)}{200 \times 10^3} = 1000$$

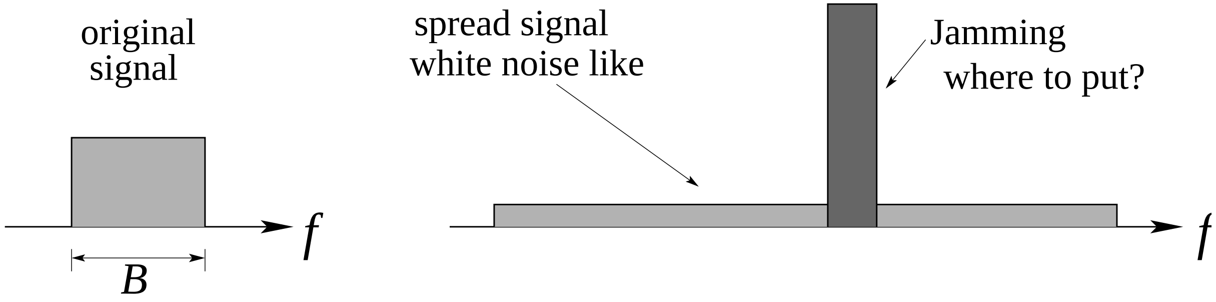
  A GSM time slot consists of 6 trailing bits, 8.25 guard bits, 26 training bits and 2 traffic bursts of 58 data bits: $b_{Tot} = 1250$ b/frame, $b_{OH} = 322$ b/frame and $\eta_f = 74.24\%$
- FDMA is 1st generation technology: a radio channel for one user, and wasted when not in use
  - It requires very few bits for overhead but system costs are high due to single channel per carrier design and costly RF bandpass filters to minimise adjacent channel interference
- TDMA is 2nd generation technology: a single carrier is shared by several users
  - Burst nature of transmission makes the handoff process simpler, since it is able to listen for other base station during idle time slots, and bandwidth on demand can be implemented
  - TDMA systems require high synchronisation overhead and guard slots to separate users
- FDMA will always be part of the system for dividing spectrum, e.g.
  - in a TDMA system, FDMA must be used to divide the total system bandwidth into radio channels and each radio channel is then TDMA for several users

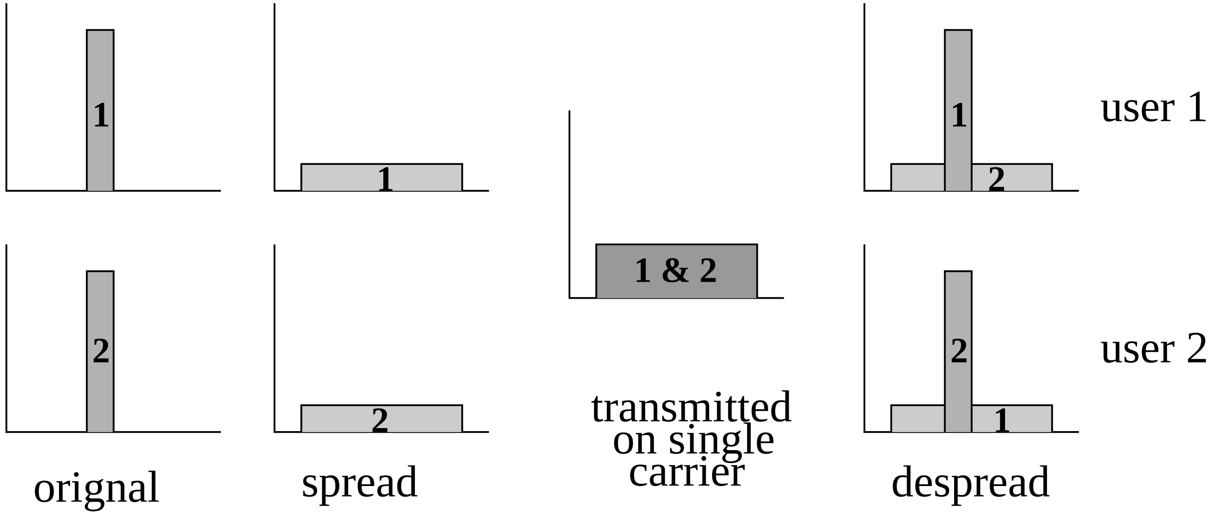
Direct sequence Spread Spectrum Modulation

- Recall that to transmit at rate f_b requires certain bandwidth B, and all schemes discussed so far try to be bandwidth efficient, as spectrum resource is extremely precious
- Image a modulation scheme which requires a bandwidth $\gg B$! Spread spectrum does this
- Original purposes of SS techniques: security and anti-jamming

  The basic idea is to spread communication signal, which is relatively narrowband, to a very wideband white noise like one

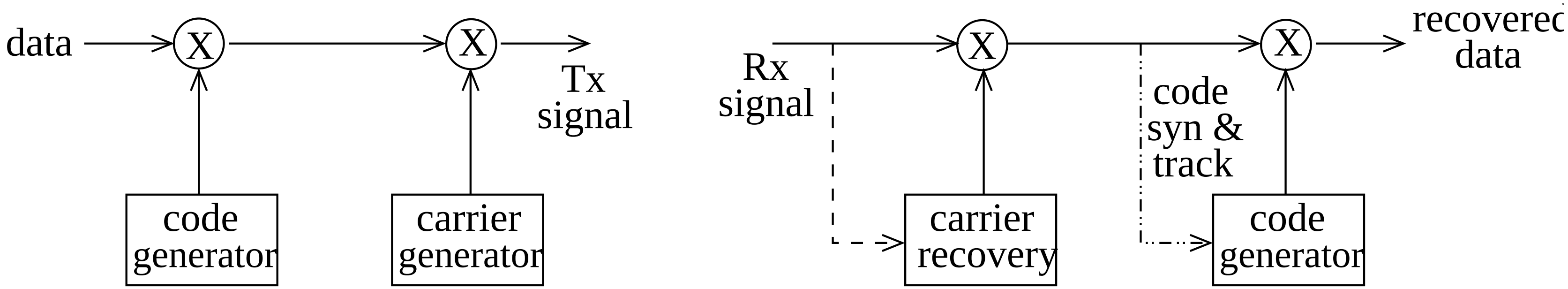
  SS as a single user scheme will be very bandwidth inefficient but it turns out to be an excellent multi-user scheme to simultaneously transmit multiple users on a single carrier, and in doing so becomes very bandwidth efficient and has a much larger capacity



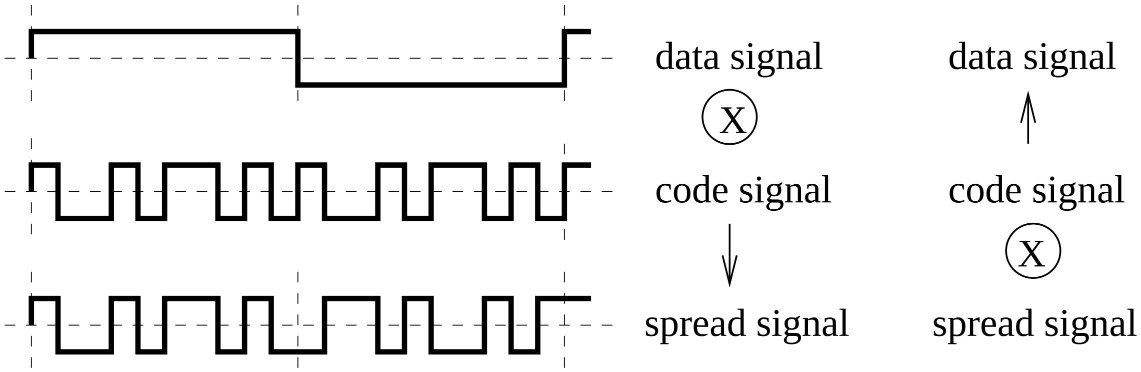


DS-SS Transceiver

- The modulator/demodulator are similar to standard ones, except bandwidth dealt with is much wider: a code generator generates a **chip** sequence of rate $f_{chip} \gg f_d$, where f_d is the data symbol rate and clock recovery is not shown



- Typically $f_{chip} = N \cdot f_d$, and N is called **spreading gain**
- The operation of spreading and despreading:



- A key feature of CDMA technology: **spreading sequences** or **codes**

Pseudo-Noise Sequences

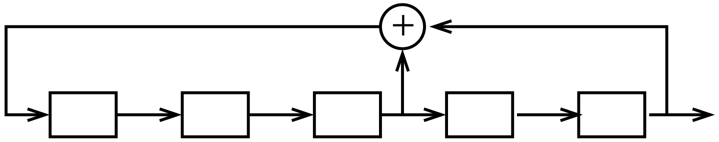
- PN sequences: are periodic binary sequences with autocorrelation exist noise-like property. Let two PN sequences of period N be $\{a_n\}_{n=0}^{N-1}$ and $\{b_n\}_{n=0}^{N-1}$

$$\text{autocorrelation:} \quad R_{aa}(k) = \frac{1}{N}\sum_{n=0}^{N-1} a_n a_{n+k} \quad \text{crosscorrelation:} \quad R_{ab}(k) = \frac{1}{N}\sum_{n=0}^{N-1} a_n b_{n+k}$$

- They can be produced with shift register feedback circuit or generator polynomial

A few rules:
- All zeros state is not allowed
- For m registers, period $N \le 2^m - 1$
- Think binary bits $0, 1$ as waveforms $+1, -1$

$g(x) = 1 + x^2 + x^5$:



- Basic requirements of spreading codes
  - A code should have good **autocorrelation** property (ideally, an impulse at offset $k = 0$). Then **code synchronisation** and tracking will be easy: just repeatedly shift the code one chip and do the correlation with the received signal until the correlation peaks
  - For any two signature codes, their **crosscorrelation** should be very small (ideally, zero over all values of k). Then **multi-user interference** (MUI) will be small

m-Sequences and Gold Codes

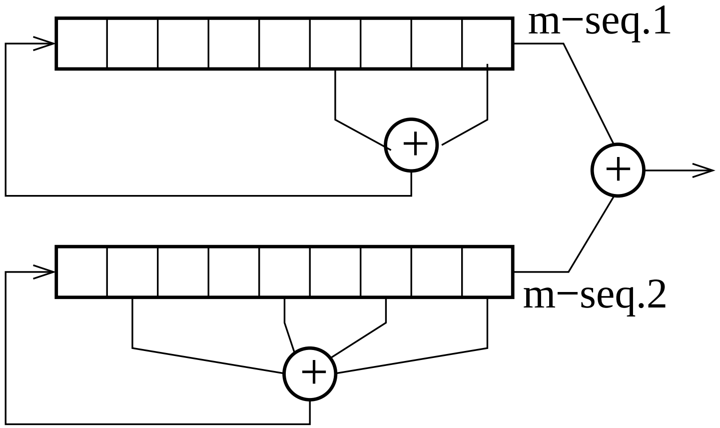
- Recall that, for m registers, sequence period $N \leq 2^m - 1$. Those PN sequences which have a maximal period or length $N = 2^m - 1$ are called maximal length sequences or **m**-sequences
- Autocorrelation of an **m**-sequence:

$$R_{aa}(k) = \begin{cases} 1, & k = lN \\ -\frac{1}{N}, & k \neq lN \end{cases}$$

  - Excellent autocorrelation property but relatively poor crosscorrelation property
  - Size of codes for a m is small (usually $<< N$), thus small multi-user capacity
- Gold codes: given a set of **m**-sequences, certain pairs have three-value crosscorrelation function $(-1, -t(m), t(m) - 2)$, with factor $\frac{1}{N}$ omitted

$$t(m) = \begin{cases} 2^{(m+1)/2} + 1, & m \quad \text{odd} \\ 2^{(m+2)/2} + 1, & m \quad \text{even} \end{cases}$$

  maximum of which is smaller than those of the rest **m**-sequences. These are called preferred pairs and are used to generate Gold codes
  - Lower peak crosscorrelation than m-sequences and generally lower crosscorrelation



- Repeating for all possible cyclically shifted modulo-2 additions of a preferred pair results in N sequences, plus original preferred pair → size of Gold codes from a preferred pair is $N + 2$

Comparison

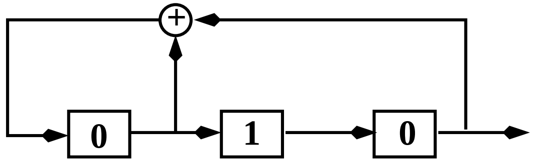
The table compares **m**-sequences with Gold codes, where m is the number of registers, N the code length, and peak level is the maximum crosscorrelation value (with the factor $\frac{1}{N}$ omitted)

m	N	m-sequences Set size	 Peak level	Gold codes Set size	 Peak level
3	7	2	5	9	5
4	15	2	9	17	9
5	31	6	11	33	9
6	63	6	23	65	17
7	127	18	41	129	17
8	255	16	95	257	33
9	511	48	113	513	33
10	1023	60	383	1025	65
11	2047	176	287	2049	65
12	4095	144	1407	4097	129

m-Sequence Example

clock	register state			output	offset k						
0	0	1	0	code	0	1	2	3	4	5	6
1	0	0	1	**0**	1	-1	-1	-1	1	1	-1
2	1	0	0	**1**	-1	1	-1	-1	-1	1	1
3	1	1	0	**0**	1	-1	1	-1	-1	-1	1
4	1	1	1	**0**	1	1	-1	1	-1	-1	-1
5	0	1	1	**1**	-1	1	1	-1	1	-1	-1
6	1	0	1	**1**	-1	-1	1	1	-1	1	-1
7	0	1	0	**1**	-1	-1	-1	1	1	-1	1

The shift register feedback circuit for the generating polynomial $g(x) = 1 + x^2 + x^3$ with the initial condition:



There are $m = 3$ shift register stages and the period of **m**-sequences is $N = 2^m - 1 = 7$.

Autocorrelation function:

$$R_{aa}(k) = \frac{1}{N} \sum_{n=0}^{N-1} a_n a_{n+k} \quad \text{with} \quad N = 7$$

$$R_{aa}(0) = \frac{1}{7}(1 \times 1 + (-1) \times (-1) + 1 \times 1 + 1 \times 1 + (-1) \times (-1) + (-1) \times (-1) + (-1) \times (-1)) = \frac{1}{7} \times 7 = 1$$

$$R_{aa}(1) = \frac{1}{7}(1 \times (-1) + (-1) \times 1 + 1 \times (-1) + 1 \times 1 + (-1) \times 1 + (-1) \times (-1) + (-1) \times (-1))$$

$$= \frac{1}{7}(-1 - 1 - 1 + 1 - 1 + 1 + 1) = \frac{1}{7} \times (-1) = -\frac{1}{7}$$

$$\vdots$$

$$R_{aa}(6) = \frac{1}{7}(1 \times (-1) + (-1) \times 1 + 1 \times 1 + 1 \times (-1) + (-1) \times (-1) + (-1) \times (-1) + (-1) \times 1)$$

$$= \frac{1}{7}(-1 - 1 + 1 - 1 + 1 + 1 - 1) = \frac{1}{7} \times (-1) = -\frac{1}{7}$$

Orthogonal Codes

- Orthogonal codes: these codes are orthogonal, i.e. crosscorrelation at lag or offset $k = 0$ is zero
- In perfect synchronisation, there is no MUI, but in practice autocorrelation and crosscorrelation of codes at $k \neq 0$ are also important. Note that multipath will destroy orthogonality
- Walsh codes: apply Hadamard transform

$$\mathbf{H}_1 = [0] \quad \mathbf{H}_{2n} = \left[\begin{array}{cc} \mathbf{H}_n & \mathbf{H}_n \\ \mathbf{H}_n & \overline{\mathbf{H}}_n \end{array} \right] \quad \text{e.g.} \quad \mathbf{H}_2 = \left[\begin{array}{cc} 0 & 0 \\ 0 & 1 \end{array} \right], \quad \mathbf{H}_4 = \left[\begin{array}{cccc} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{array} \right], \quad \cdots$$

- Note that columns of $\mathbf{H}_n$ are orthogonal and the same for rows (remember $0, 1 \longrightarrow +1, -1$, try this on $\mathbf{H}_4$ and verify orthogonality)
- For Walsh codes, $N = 2, 4, 8, 16$ etc. and, for code length N, there are N orthogonal codes (multi-user capacity similar to Gold codes)

  But autocorrelation and crosscorrelation at $k \neq 0$ are considerably larger than Gold codes
- Orthogonal Gold codes: by carefully attaching an additional "0" to original Gold codes, the resulting codes become orthogonal with much better autocorrelation characteristics than Walsh codes
- OVSF: codes with **orthogonal variable spreading factors** to support different rates
- Codes with large **zero correlation zone**: no need to achieve precise synchronisation

Summary

- Duplexing: frequency division duplexing, time division duplexing, “space division” duplexing

- Multiple access schemes: FDMA, TDMA, CDMA, SDMA

- Direct-sequence spread-spectrum modulation: principle and basic transceiver structure

- Spread sequences or signature codes and multiuser capacity

  PN sequences: maximal length sequences, Gold codes, how to generate them

  Orthogonal codes: Walsh codes, orthogonal Gold codes, how to generate them