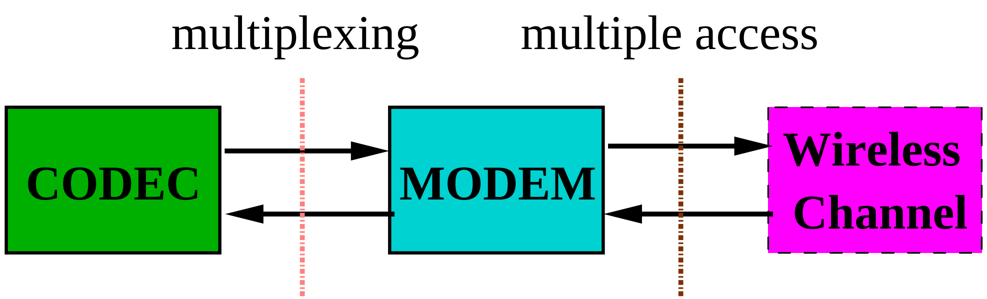
Revision of Lecture Eighteen

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

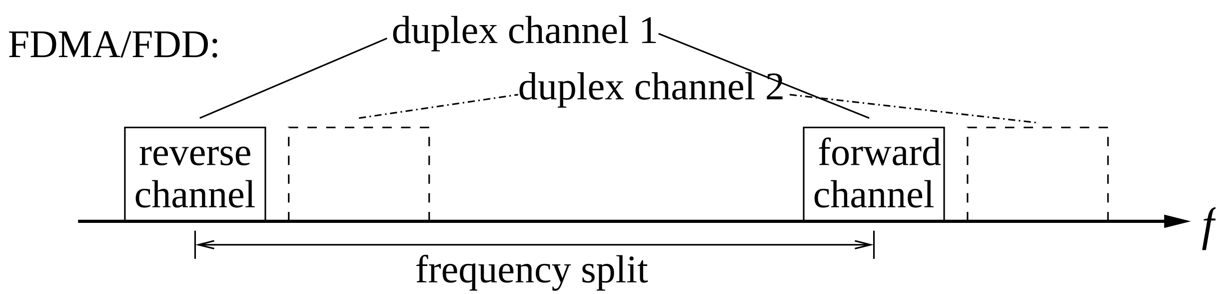


- We will also discuss **medium access control**, MAC, the important sublayer linking physical layer, PHY, and network layer

Multiple Access

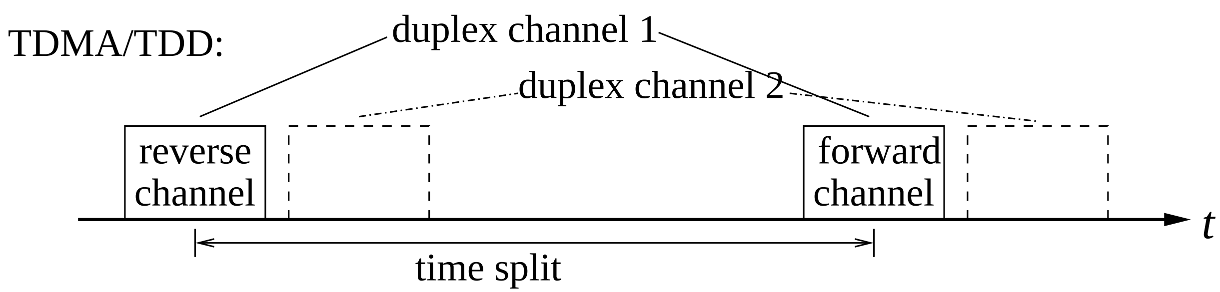
- **Multiple access**: allow many users to share simultaneously a finite amount of radio spectrum
- In terms of network protocol architecture: the medium access control which is part of data link layer
- **Duplexing**: mobile can simultaneously sent to and receive from base station. A duplexing channel consists of two simplex channels
- **Frequency division duplexing**: employ two distinct frequency bands, one for forward channel (base to mobile) and the other for reverse channel (mobile to base)

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



- **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



Multiple Access Techniques

- **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

- **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

- **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

- **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 further enhances efficiency of spectrum utilisation

Multiple Access Techniques (continue)

- Channels are dynamically allocated and how to make reservation to gain an access may involve a contention process
- FDMA and TDMA have a **hard capacity**: no more user can access after reaching the capacity while CDMA and SDMA have **soft capacity**: they allow more users at a cost of gradual degraded quality

  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 can identify uplink channel and send it to mobile who may then use it as its (downlink) channel

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 $\eta_f = 74.24\%$

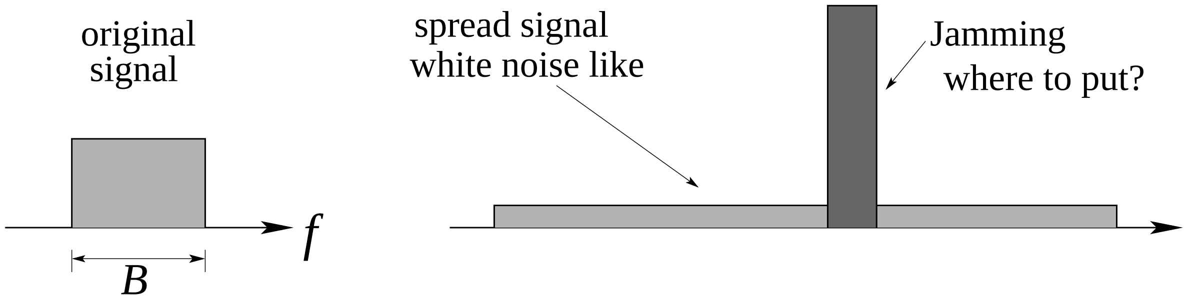
- FDMA is 1st generation technology: a radio channel for one user and, when not in use, becomes wasted. It requires very few bits for overhead but system costs are high due to single channel per carrier design and costly RF bandpass filters to minimise adjacent channel interference
- TDMA is 2nd generation technology: a single carrier is shared by several users. The burst nature of transmission makes the handoff process simpler, since it is able to listen for other base station during idle time slots. TDMA systems require high synchronisation overhead and guard slots to separate users. Bandwidth on demand can be implemented
- FDMA will always be part of the system for dividing spectrum, e.g. in a TDMA system, FDMA is used to divide the total system bandwidth into radio channels and each radio channel is then TDMA for several users

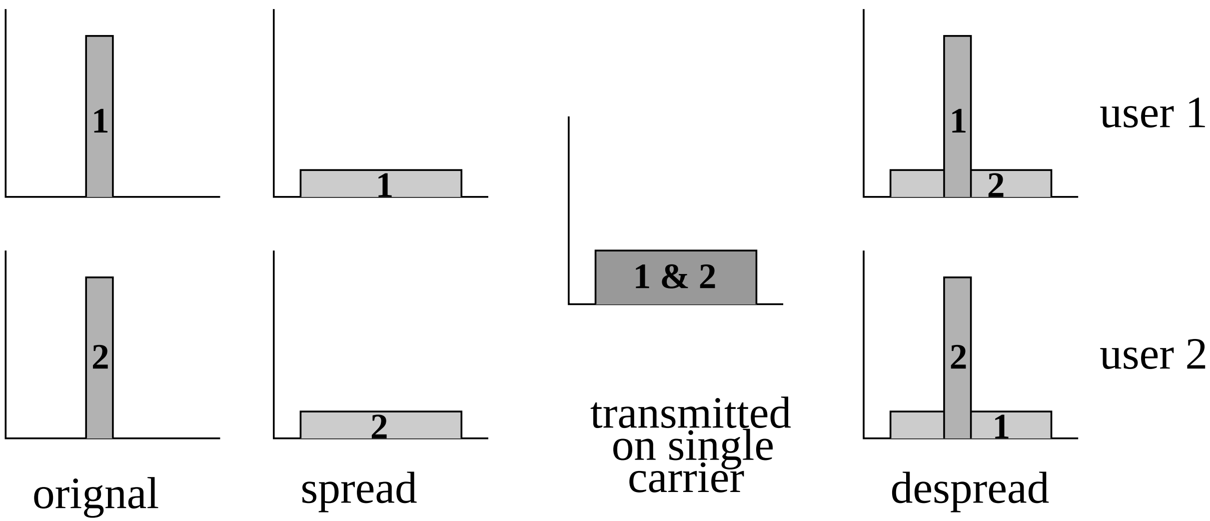
Direct sequence Spread Spectrum Modulation

- 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

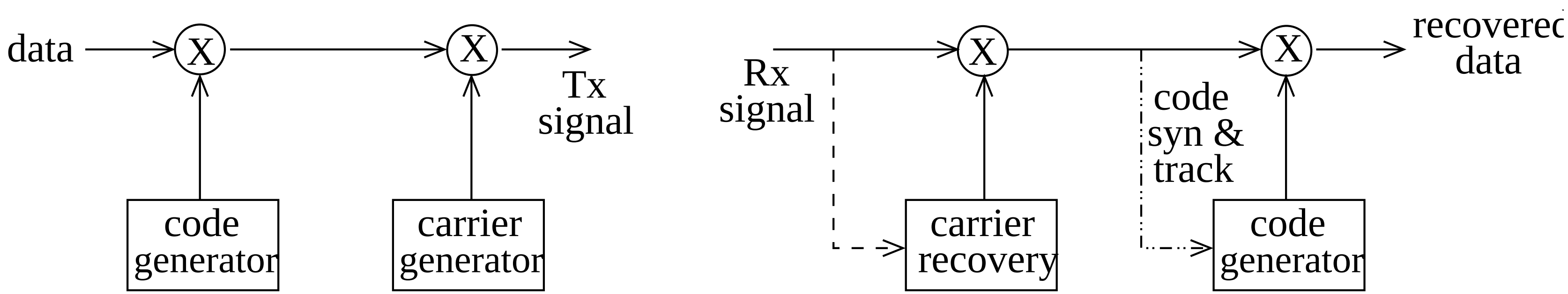
  SS as a single user scheme will be very bandwidth inefficient but it turns out to be an excellent multi-user scheme to simultaneously transmit multiple users on a single carrier, and in doing so becomes very bandwidth efficient and has a much larger capacity



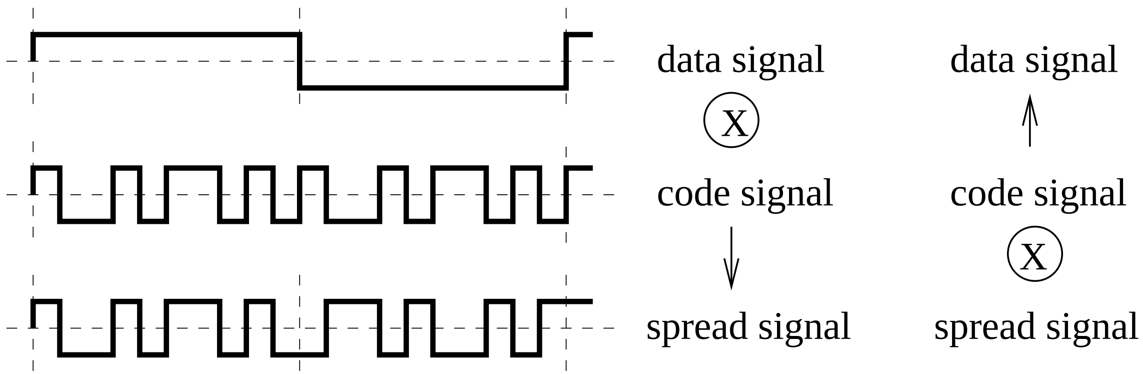


DS-SS Transceiver

- 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

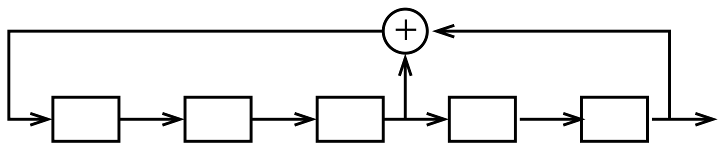
- PN sequences: are periodic binary sequences with autocorrelation exist noise-like property. Let two PN sequences of period N be $\{a_n\}_{n=0}^{N-1}$ and $\{b_n\}_{n=0}^{N-1}$

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

- 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 $N \leq 2^m - 1$
- Think binary bits $0, 1$ as waveforms $+1, -1$

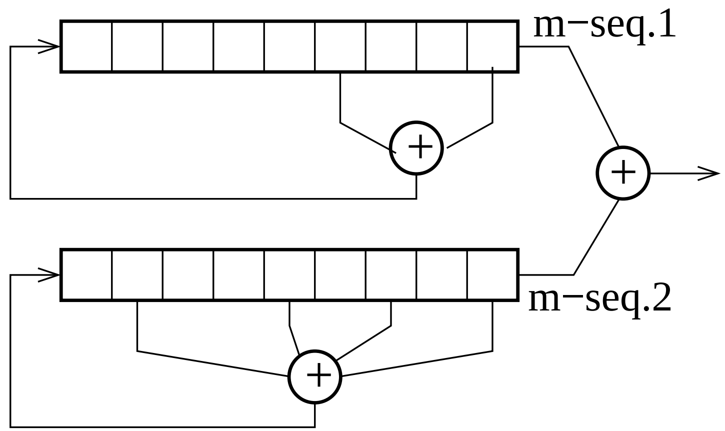
$g(x) = 1 + x^2 + x^5$:



- 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
$$t(m) = \begin{cases} 2^{(m+1)/2} + 1, & m \ \text{odd} \\ 2^{(m+2)/2} + 1, & m \ \text{even} \end{cases}$$
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 $\longrightarrow$ size of Gold codes from a preferred pair is $N + 2$

Comparison

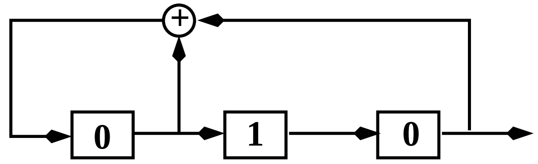
The table compares **m**-sequences with Gold codes, where m is the number of registers, N the code length, and peak level is the maximum crosscorrelation value (with the factor $\frac{1}{N}$ omitted)

m	N	m-sequences		Gold codes	
		Set size	Peak level	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

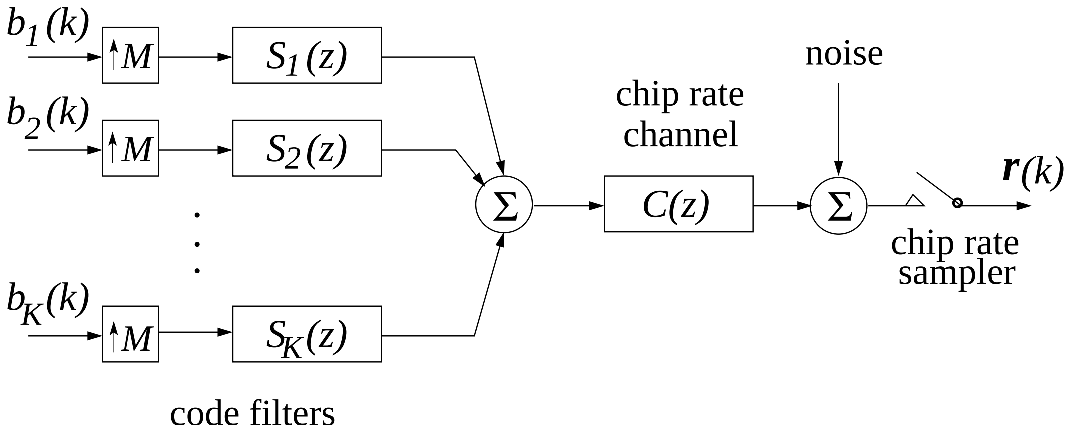
- Orthogonal codes: these codes are orthogonal, i.e. crosscorrelation at lag or offset $k = 0$ is zero
- In perfect synchronisation, there is no MUI, but in practice autocorrelation and crosscorrelation of codes at $k \neq 0$ are also important. Note that multipath will destroy orthogonality
- Walsh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

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

- 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

Multiuser Detection

- Consider downlink case (handset), where $b_i(k) \in \{\pm 1\}$ denotes k-th bit of user i, user i code $\mathbf{s}_i = [s_{i,1} \cdots s_{i,M}]^T$, the received signal vector at chip rate $\mathbf{r}(k) = [r_1(k) \cdots r_M(k)]^T$, and K is the number of users



- Assume that there is no multipath distortion, the codes are orthogonal and synchronisation is perfect. Then to detect user i data one only needs to despread $\mathbf{r}(k)$ with the code $\mathbf{s}_i$:

$$y(k) = \mathbf{s}_i^T \mathbf{r}(k) \quad \text{and} \quad \hat{b}_i(k) = \text{sgn}(y(k))$$

- This is called matched filter detection. However, when the channel distortion exists, multiuser interference becomes serious and the matched filter detection is no longer adequate
- A widely used detector is the linear detector given by

$$y(k) = \mathbf{w}^T \mathbf{r}(k) \quad \text{and} \quad \hat{b}_i(k) = \text{sgn}(y(k))$$

Note that this is similar to linear equaliser → MMSE and MBER designs, adaptive LMS and LBER

Summary

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

  Basic techniques, capacity of a multiple access scheme,

  CDMA (3rd generation technology), SDMA (4th generation technology?)

- 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

- Multiuser detection: matched filter detection, linear detector