Frequency Hopping Spread Spectrum

1. Bluetooth system

The Equipment Under Test (EUT) is the Digital Video Camera Recorder, witch has a **Bluetooth** communication module internally. **Bluetooth** is the one of the short-range wireless communication system with frequency hopping spread spectrum (FHSS). **Bluetooth Specification** is standardized by and published by **Bluetooth Special Interest Group (SIG)**. This EUT is completely applied to **The Bluetooth Specification ver. 1.1** released in February 22nd, 2001.

2. Hopping Frequency

The frequency range is 2402 MHz to 2480 MHz with spanning 79MHz. Hopping frequencies (channels) are separated by 1MHz within 20 dB bandwidth. Therefore there are 79 hopping frequencies. These hopping frequencies are selected by pseudo random sequence so that each frequency must be used equally on the average. The slot length of **Bluetooth** is separated by 625 microsecond and **Bluetooth** specifications allow a multi slots packet using these slots, up to five slots without an interval. A hopping frequency occupies over this multi slots packet and the longest occupancy is 3.125 millisecond, in case of a five-slot packet.

3. Hopping Sequence

The hopping frequencies are selected derived from the **Bluetooth** clock and the **Bluetooth BD_Address**, which is a unique ID for unit by unit.

Hopping frequencies are grouped into several segments. Each segment consists of 32 hop frequencies spanning about 64MHz. The hopping frequency selection scheme chooses a segment and visits these hops once in a random order. In case of connection mode, the selected 32-hop segment is changed by pseudo random sequence one after another. And cycling time is so long, because the code length is 2^27-1.

4. Creating connection

Short-range wireless communication network of **Bluetooth**, called piconet, is established as following. One "Master" unit searches for other "Slave" units in surrounding area, which is called "Inquiry". If at least one "Slave" is found, "Master" can try to create connection with it, which is called "Page". After the connection is established, "Master" unit controls the hopping sequence in the piconet. In this case, "Master" unit's BD_Address is used to generate hopping sequence.

2 FREQUENCY BANDS AND CHANNEL ARRANGEMENT

The Bluetooth system is operating in the 2.4 GHz ISM (Industrial Scientific Medicine) band. In a vast majority of countries around the world the range of this frequency band is 2400 - 2483.5 MHz. Some countries have however national limitations in the frequency range. In order to comply with these national limitations, special frequency hopping algorithms have been specified for these countries. It should be noted that products implementing the reduced frequency band <u>will not</u> work with products implementing the full band. The products implementing the reduced frequency band must therefore be considered as local versions for a single market. The Bluetooth SIG has launched a campaign to overcome these difficulties and reach total harmonization of the frequency band.

Geography	Regulatory Range	RF Channels
USA, Europe and most other countries[1]	2.400-2.4835 GHz	f=2402+k MHz, k=0,…,78

Table 2.1: Operating frequency bands

Note 1. The Bluetooth Specification includes a special frequency hopping pattern to provide provisions for compliance with national limitations like in France. The frequency range for France is 2.4465 - 2.4835 GHz and the corresponding RF channels are f = 2454 + k MHz, k= 0,...,22. .

Channel spacing is 1 MHz. In order to comply with out-of-band regulations in each country, a guard band is used at the lower and upper band edge.

Geography	Lower Guard Band	Upper Guard Band
USA, Europe and most other countries	2 MHz	3.5 MHz

Table 2.2: Guard Bands

Baseband Specification

2 PHYSICAL CHANNEL

2.1 CHANNEL DEFINITION

The channel is represented by a pseudo-random hopping sequence hopping through the 79 or 23 RF channels. The hopping sequence is unique for the piconet and is determined by the Bluetooth device address of the master; the phase in the hopping sequence is determined by the Bluetooth clock of the master. The channel is divided into time slots where each slot corresponds to an RF hop frequency. Consecutive hops correspond to different RF hop frequencies. The nominal hop rate is 1600 hops/s. All Bluetooth units participating in the piconet are time- and hop-synchronized to the channel.

2.2 TIME SLOTS

The channel is divided into time slots, each 625 μs in length. The time slots are numbered according to the Bluetooth clock of the piconet master. The slot numbering ranges from 0 to 2^{27}-1 and is cyclic with a cycle length of 2^{27}.

In the time slots, master and slave can transmit packets.

A TDD scheme is used where master and slave alternatively transmit, see . The master shall start its transmission in even-numbered time slots only, and the slave shall start its transmission in odd-numbered time slots only. The packet start shall be aligned with the slot start. Packets transmitted by the master or the slave may extend over up to five time slots.

The RF hop frequency shall remain fixed for the duration of the packet. For a single packet, the RF hop frequency to be used is derived from the current Bluetooth clock value. For a multi-slot packet, the RF hop frequency to be used for the entire packet is derived from the Bluetooth clock value in the first slot of the packet. The RF hop frequency in the first slot after a multi-slot packet shall use the frequency as determined by the current Bluetooth clock value. illustrates the hop definition on single- and multi-slot packets. If a packet occupies more than one time slot, the hop frequency applied shall be the hop frequency as applied in the time slot where the packet transmission was started.
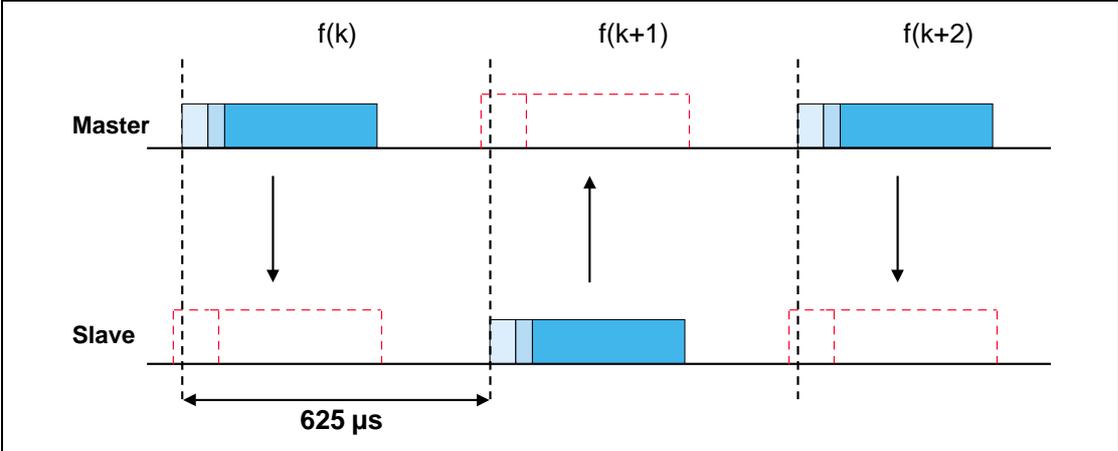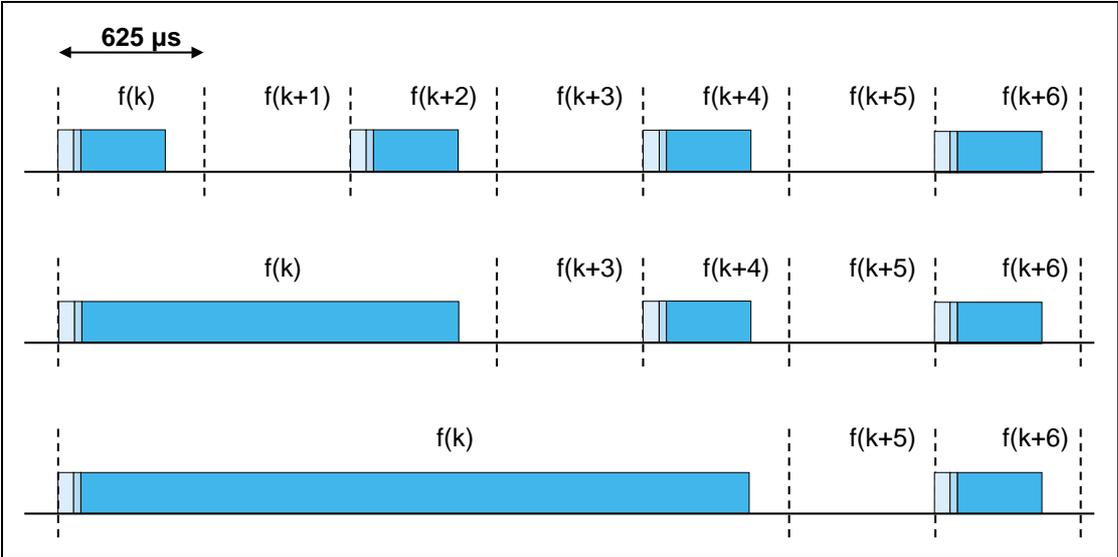
Figure 2.1: TDD and timing

Figure 2.2: Multi-slot packets

11 HOP SELECTION

In total, 10 types of hopping sequences are defined – five for the 79-hop and five for the 23-hop system, respectively. Using the notation of parentheses () for figures related to the 23-hop system, these sequences are:

- A **page hopping sequence** with 32 (16) unique wake-up frequencies distributed equally over the 79 (23) MHz, with a period length of 32 (16);

- A **page response sequence** covering 32 (16) unique response frequencies that all are in an one-to-one correspondence to the current page hopping sequence. The master and slave use different rules to obtain the same sequence;

- An **inquiry sequence** with 32 (16) unique wake-up frequencies distributed equally over the 79 (23) MHz, with a period length of 32 (16);

- A **inquiry response sequence** covering 32 (16) unique response frequencies that all are in an one-to-one correspondence to the current inquiry hopping sequence.

- A **channel hopping sequence** which has a very long period length, which does not show repetitive patterns over a short time interval, but which distributes the hop frequencies equally over the 79 (23) MHz during a short time interval;

For the page hopping sequence, it is important that we can easily shift the phase forward or backward, so we need a 1-1 mapping from a counter to the hop frequencies. For each case, both a hop sequence from master to slave and from slave to master are required.

The inquiry and inquiry response sequences always utilizes the GIAC LAP as lower address part and the DCI (Section 5.4 on page 72) as upper address part in deriving the hopping sequence, even if it concerns a DIAC inquiry.

11.1 GENERAL SELECTION SCHEME

The selection scheme consists of two parts:

- selecting a sequence;

- mapping this sequence on the hop frequencies;

The general block diagram of the hop selection scheme is shown in Figure 11.1 on page 127. The mapping from the input to a particular hop frequency is performed in the selection box. Basically, the input is the native clock and the current address. In **CONNECTION** state, the native clock (CLKN) is modified by an offset to equal the master clock (CLK). Only the 27 MSBs of the clock are used. In the **page** and **inquiry** substates, all 28 bits of the clock are used. However, in **page** substate the native clock will be modified to the master's estimate of the paged unit.

The address input consists of 28 bits, i.e., the entire LAP and the 4 LSBs of the UAP. In **CONNECTION** state, the address of the master is used. In **page** substate the address of the paged unit is used. When in **inquiry** substate, the UAP/LAP corresponding to the GIAC is used. The output constitutes a pseudo-random sequence, either covering 79 hop or 23 hops, depending on the state.
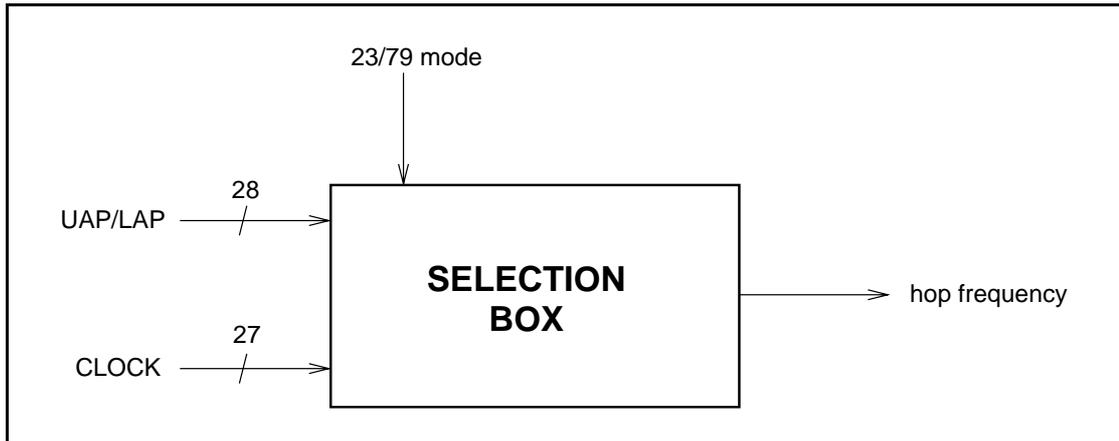
Figure 11.1: General block diagram of hop selection scheme.

For the 79-hop system, the selection scheme chooses a segment of 32 hop frequencies spanning about 64 MHz and visits these hops once in a random order. Next, a different 32-hop segment is chosen, etc. In case of the **page, page scan,** or **page response** substates, the same 32-hop segment is used all the time (the segment is selected by the address; different units will have different paging segments). In connection state, the output constitutes a pseudo-random sequence that slides through the 79 hops or 23 hops, depending on the selected hop system. For the 23-hop systems, the segment size is 16. The principle is depicted in Figure 11.2
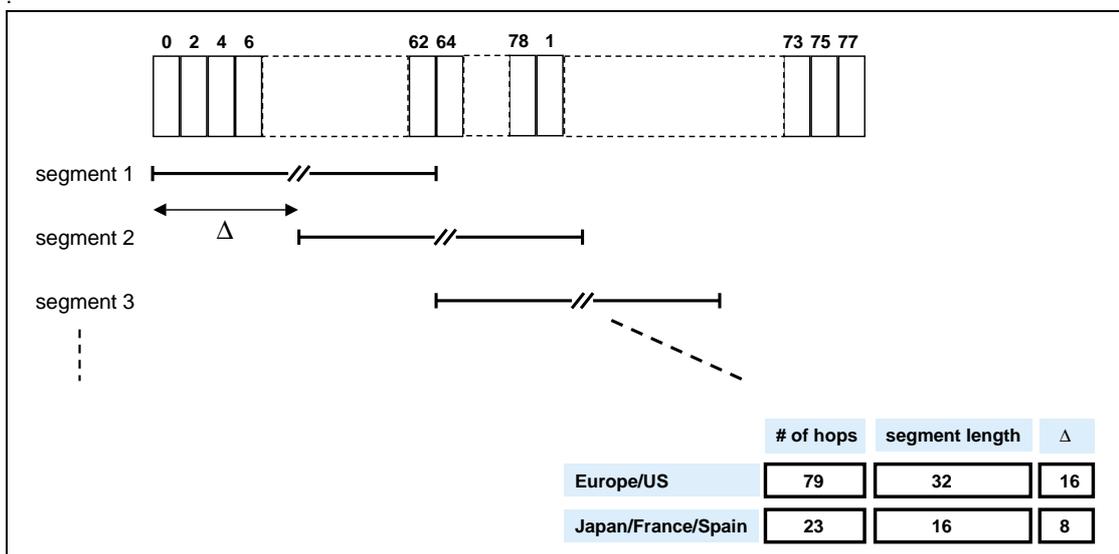
	# of hops	segment length	Δ
Europe/US	79	32	16
Japan/France/Spain	23	16	8

Figure 11.2: Hop selection scheme in CONNECTION state.

11.2 SELECTION KERNEL

The hop selection kernels for the 79 hop system and the 23 hop system are shown in Figure 11.3 on page 128 and Figure 11.4 on page 128, respectively. The X input determines the phase in the 32-hop segment, whereas Y1 and Y2 selects between master-to-slave and slave-to-master transmission. The inputs A to D determine the ordering within the segment, the inputs E and F determine the mapping onto the hop frequencies. The kernel addresses a register containing the hop frequencies. This list should be created such that first all even hop frequencies are listed and then all odd hop frequencies. In this way, a 32-hop segment spans about 64 MHz, whereas a 16-hop segment spans the entire 23-MHz.
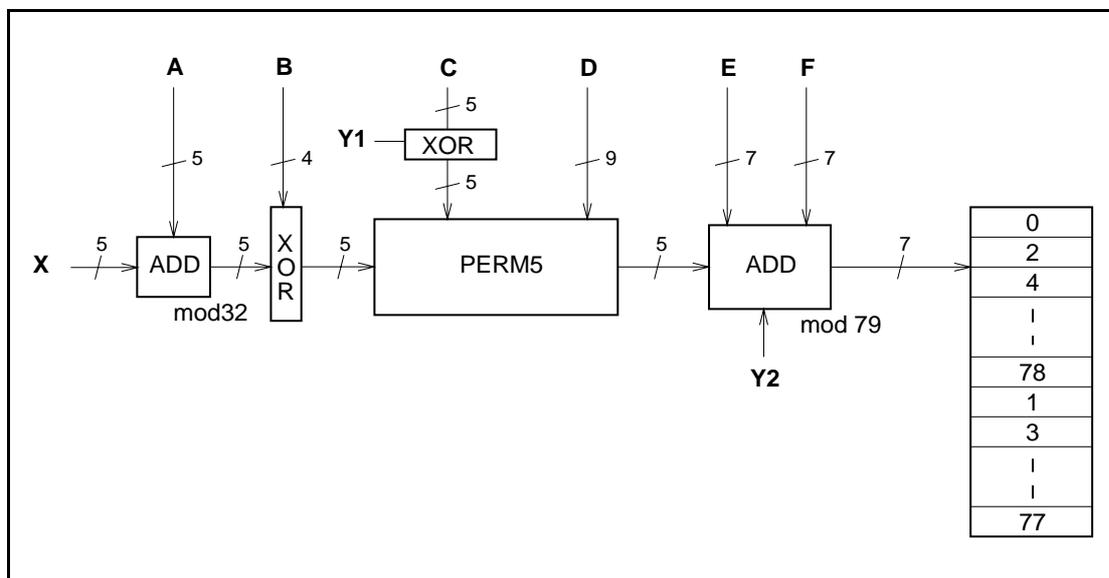
Figure 11.3: Block diagram of hop selection kernel for the 79-hop system.
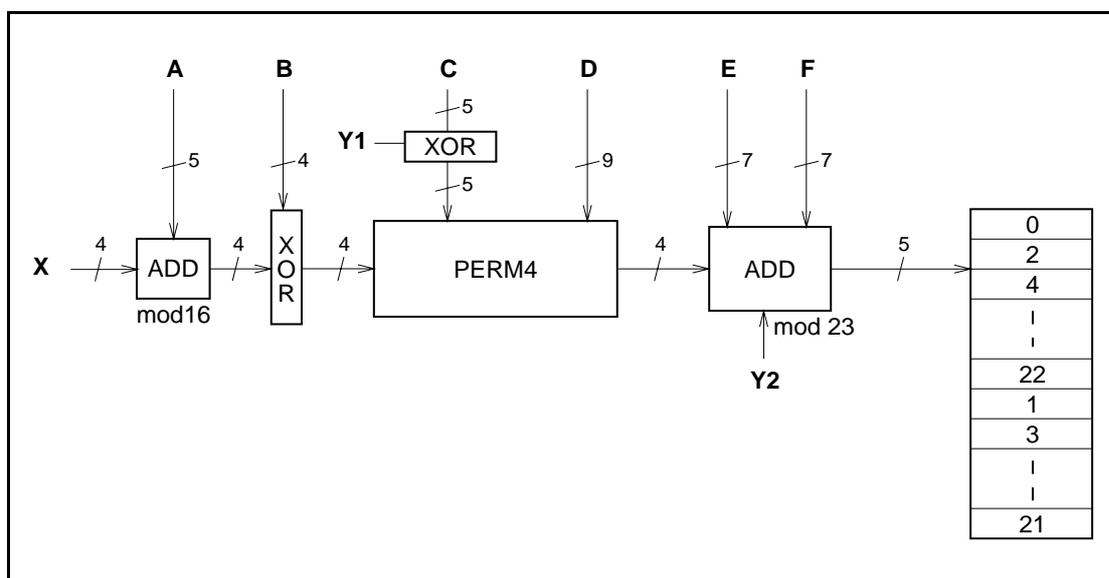

Figure 11.4: Block diagram of hop selection kernel for the 23-hop system.

The selection procedure consists of an addition, an XOR operation, a permutation operation, an addition, and finally a register selection. In the remainder of this chapter, the notation A_i is used for bit i of the BD_ADDR.

11.2.1 First addition operation

The first addition operation only adds a constant to the phase and applies a modulo 32 or a modulo 16 operation. For the page hopping sequence, the first addition is redundant since it only changes the phase within the segment. However, when different segments are concatenated (as in the channel hopping sequence), the first addition operation will have an impact on the resulting sequence.

11.2.2 XOR operation

Let Z' denote the output of the first addition. In the XOR operation, the four LSBs of Z' are modulo-2 added to the address bits A_{22-19}. The operation is illustrated in .
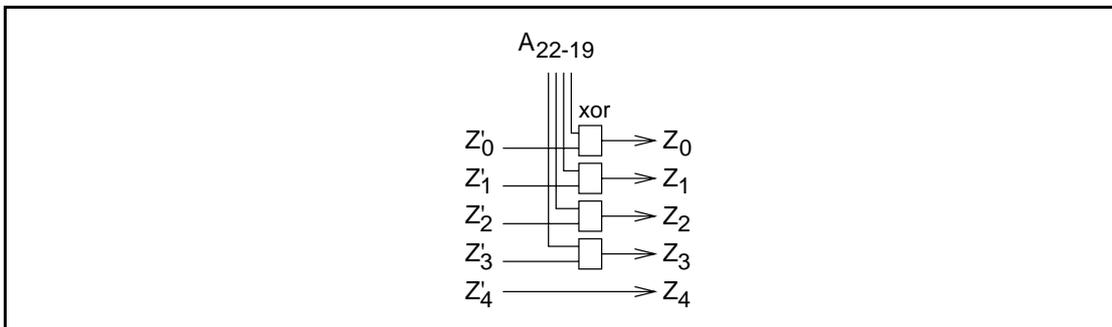

Figure 11.5: XOR operation for the 79-hop system. The 23-hop system is the same except for the Z'_4/Z_4 wire that does not exist.

11.2.3 Permutation operation

The permutation operation involves the switching from 5 inputs to 5 outputs for the 79 hop system and from 4 inputs to 4 outputs for 23 hop system, in a manner controlled by the control word. In Figure 11.6 on page 131 and Figure 11.7 on page 131 the permutation or switching box is shown. It consists of 7 stages of butterfly operations. Table 11.1 and Table 11.2 shows the control of the butterflies by the control signals P. Note that P_{0-8} corresponds to D_{0-8}, and, P_{i+9} corresponds to $C_i \oplus Y1$ for $i = 0...4$ in Figure 11.3 and Figure 11.4.

Control signal	Butterfly		Control signal	Butterfly
P_0	$\{Z_0, Z_1\}$		P_8	$\{Z1, Z4\}$
P_1	$\{Z_2, Z_3\}$		P_9	$\{Z_0, Z_3\}$
P_2	$\{Z_1, Z_2\}$		P_{10}	$\{Z_2, Z_4\}$
P_3	$\{Z_3, Z_4\}$		P_{11}	$\{Z_1, Z_3\}$
P_4	$\{Z_0, Z_4\}$		P_{12}	$\{Z_0, Z_3\}$
P_5	$\{Z_1, Z_3\}$		P_{13}	$\{Z_1, Z_2\}$
P_6	$\{Z_0, Z_2\}$			
P_7	$\{Z_3, Z_4\}$			

Table 11.1: Control of the butterflies for the 79 hop system

Control signal	Butterfly		Control signal	Butterfly
P_0	$\{Z_0, Z_1\}$		P_8	$\{Z_0, Z_2\}$
P_1	$\{Z_2, Z_3\}$		P_9	$\{Z_1, Z_3\}$
P_2	$\{Z_0, Z_3\}$		P_{10}	$\{Z_0, Z_3\}$
P_3	$\{Z_1, Z_2\}$		P_{11}	$\{Z_1, Z_2\}$
P_4	$\{Z_0, Z_2\}$		P_{12}	$\{Z_0, Z_1\}$
P_5	$\{Z_1, Z_3\}$		P_{13}	$\{Z_2, Z_3\}$
P_6	$\{Z_0, Z_1\}$			
P_7	$\{Z_2, Z_3\}$			

Table 11.2: Control of the butterflies for the 23 hop system

The Z input is the output of the XOR operation as described in the previous section. The butterfly operation can be implemented with multiplexers as depicted in Figure 11.8 on page 131.
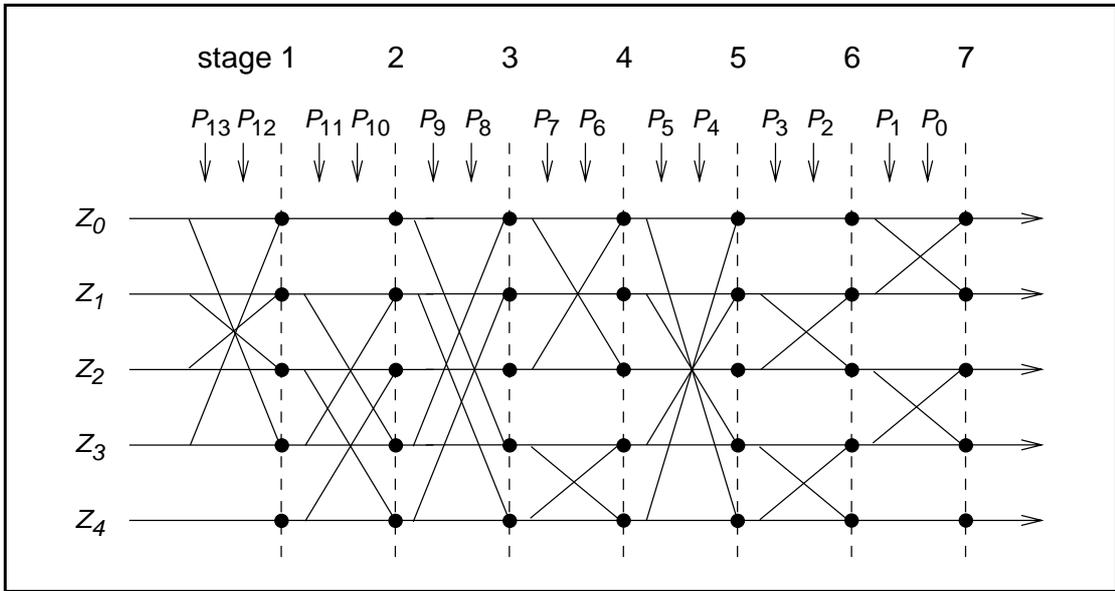
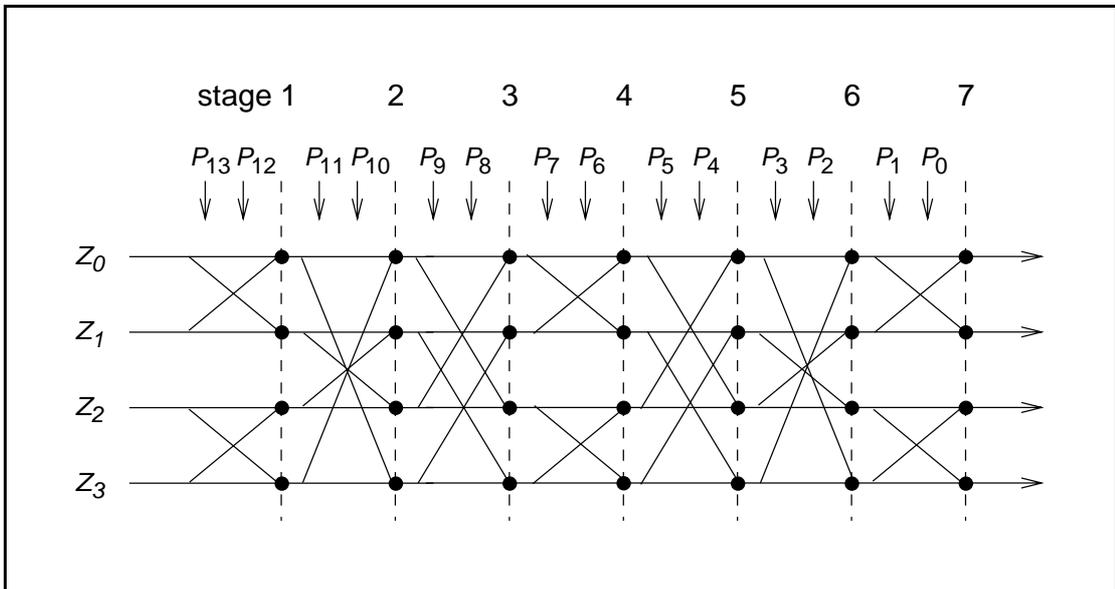Figure 11.6: Permutation operation for the 79 hop system.

Figure 11.7: Permutation operation for the 23 hop system.
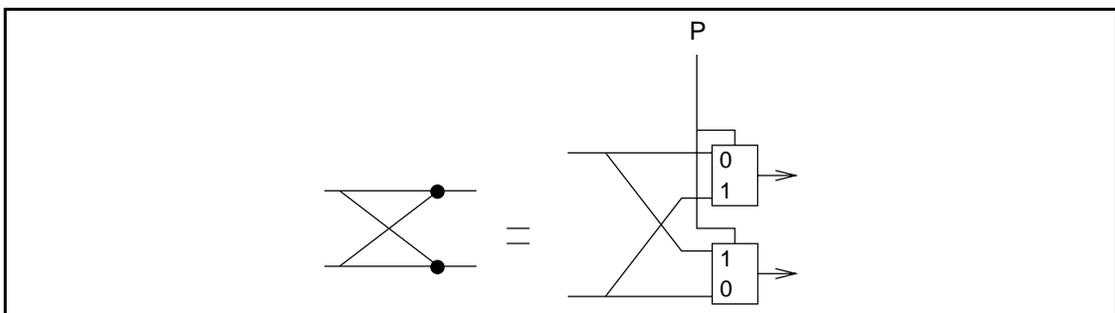
Figure 11.8: Butterfly implementation.

11.2.4 Second addition operation

The addition operation only adds a constant to the output of the permutation operation. As a result, the 16-hop or 32-hop segment is mapped differently on the hop frequencies. The addition is applied modulo 79 or modulo 23 depending on the system type (Europe/US vs. others).

11.2.5 Register bank

The output of the adder addresses a bank of 79 or 23 registers. The registers are loaded with the synthesizer code words corresponding to the hop frequencies 0 to 78 or 0 to 22. Note that the upper half of the bank contains the even hop frequencies, whereas the lower half of the bank contains the odd hop frequencies.

11.3   CONTROL WORD

In the following section X_{j-i}, $i<j$, will denote bits i, $i+1$,...,j of the bit vector X. By convention, X_0 is the least significant bit of the vector X.

The control word P of the kernel is controlled by the overall control signals X, Y1, Y2, and A to F as illustrated in Figure 11.3 on page 128 and Figure 11.4 on page 128. During paging and inquiry, the inputs A to E use the address values as given in the corresponding columns of Table 11.3 on page 133 and Table 11.4 on page 133. In addition, the inputs X, Y1 and Y2 are used. The F input is unused. In the 79-hop system, the clock bits CLK_{6-2} (i.e., input X) specifies the phase within the length 32 sequence, while for the 23-hop system, CLK_{5-2} specifies the phase within the length 16 sequence. For both systems, CLK_1 (i.e., inputs Y1 and Y2) is used to select between TX and RX. The address inputs determine the sequence order within segments. The final mapping onto the hop frequencies is determined by the register contents.

In the following we will distinguish between three types of clocks: the piconet's master clock, the Bluetooth unit's native clock, and the clock estimate of a paged Bluetooth unit. These types are marked in the following way:

1. CLK_{27-0}:   Master clock of the current piconet.
2. $CLKN_{27-0}$:   Native clock of the unit.
3. $CLKE_{27-0}$:   The paging unit's estimate of the paged unit's native clock.

During the **CONNECTION** state, the inputs A, C and D result from the address bits being bit-wise XORed with the clock bits as shown in the "Connection state" column of Table 11.3 on page 133 and Table 11.4 on page 133 (the two MSBs are XORed together, the two second MSBs are XORed together, etc.). Consequently, after every 32 (16) time slots, a new length 32 (16) segment is selected in the 79-hop (23-hop) system. The sequence order within a specific