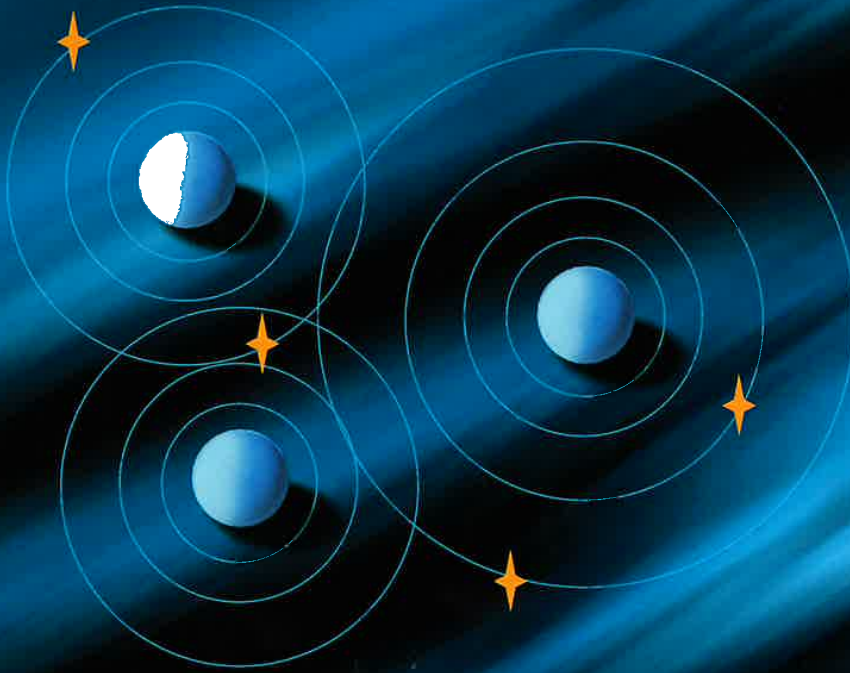




WIRELESS ACCESS NETWORKS

Fixed Wireless Access and WLL Networks
– Design and Operation

MARTIN P. CLARK

Wireless Access Networks

Fixed Wireless Access and WLL
Networks — Design and Operation

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Contents

Acknowledgements	xi
 <i>Part I Fundamentals of Fixed Wireless</i>	 1
1. The Case for Fixed Wireless Networks	3
1.1 Radio	3
1.2 The Use and Advantages of Radio for Fixed Network Access	4
1.3 The Time to Consider Installing a Fixed Wireless Access Network	5
1.4 The Coverage Offered by Wireless	5
1.5 Radio as a Means of Providing High Bit Rate Access Lines	5
1.6 Wireless Technology Allows for a 'Pay-as-you-build' Network Structure	6
1.7 Wireless as a Means of Access Line 'Back-up'	6
1.8 Radio as an Ideal Mechanism for Access Port Concentration or Multiplexing	8
1.9 Fixed Wireless Access is More Reliable than Mobile Telephony!	11
1.10 Applications of Fixed Wireless Access for Public Telecommunications Services	12
1.11 Economics of Fixed Wireless Access	13
1.12 Critical Factors Affecting the Economic Viability of Fixed Wireless Access	16
1.13 Alternative Technologies for the 'Local Loop'	17
1.14 Unbundled Access — A Serious Competitor to Fixed Wireless Access Networks?	18
1.15 Objections to the Use of Radio	20
1.16 Commercial Benefits of WLL Deployment in Public Networks	21
 2. Radio Communication, The Radio Spectrum and its Management	 23
2.1 Radio Communication	23
2.2 The Radio Communications Spectrum	23
2.3 Spectrum Management	24
2.4 The Differing Regional Structure of the Radio Spectrum	26
2.5 One-Way Radio Communication and Introduction to Radio Channels	28
2.6 Two-Way (Duplex) Radio Communication	30
2.7 Half-Duplex Communication and Time Division Multiplexing	32
2.8 Bandwidth — Determines the Capacity of a Radio Channel	33
2.9 The Spectral Mask	34
2.10 Spurious Emission	36
2.11 Authorised Uses of Radio and the Regulations Governing Use	37
2.12 Satellite Transmission Management	38
 3. Point-to-Point (PTP) and Point-to-Multipoint (PMP) Wireless Systems & Antennas	 41
3.1 Characteristics of Wireless Systems	41

3.2	Point-to-Point (PTP) Radio Systems	42
3.3	Any-to-Any Radio Systems	43
3.4	Point-To-Multipoint (PMP) Radio Systems	44
3.5	The Directionality, Gain and Lobe Diagram of an Antenna	45
3.6	High Gain Antennas Used in PTP Applications	47
3.7	Point-To-Point Antenna Diagram and Gain	49
3.8	Base Station Antennas in PMP Systems	52
3.9	Other Types of Antennas	53
4.	Radio Modulation	57
4.1	Radio Modulation and the Radio 'Modem'	57
4.2	The Basic Methods of Modulation	59
4.3	High Bit Rate Modems and Higher Modulation or Multilevel Transmission	64
4.4	Modem 'Constellations'	65
4.5	Frequency Division Multiplexing (FDM)	67
5.	Multiple Access Schemes for Point-to-Multipoint Operation	69
5.1	Multiple Access Schemes used in PMP Radio Systems	69
5.2	FDMA (Frequency Division Multiple Access)	70
5.3	TDMA (Time Division Multiple Access)	72
5.4	Frequency Hopping — A Hybrid Form of FDMA and TDMA	75
5.5	CDMA (Code Division Multiple Access)	76
5.6	Relative Strengths of the Different 'Multiple Access' Methodologies	77
5.7	Broadcast Systems and PMP	78
<i>Part II</i>	<i>System and Network Design</i>	79
6.	Basic Radio System Design and Functionality	81
6.1	Basic System Components	81
6.2	Antenna	82
6.3	Waveguide	88
6.4	Outdoor Unit (ODU) or Radio Transceiver	90
6.5	Antenna Alignment	94
6.6	Qualities of a Good Outdoor Unit (Radio Transceiver)	95
6.7	Indoor-to-Outdoor Cabling	104
6.8	Indoor Unit (IDU) or Radio Modem	105
6.9	Radio Repeaters	112
7.	Radio Propagation, System Range, Reliability and Availability	115
7.1	The Reliability, 'Range' and 'Availability' of a Radio System	115
7.2	The Concept of 'Fade Margin'	119
7.3	ITU-R 'Transmission Loss Concept' (ITU-R Recommendation P.341)	119
7.4	Radio Wave Propagation	123
7.5	Free Space Transmission Loss — The Expected Received Signal Level in Good Weather	125
7.6	Path Losses Relative to Free-Space (L_m) in 'Line-of-Sight' Radio Systems	126

7.7	Radio Noise	135
7.8	Summary — Radio System Range and Availability and the Need to be able to Predict Radio Signal Strength	137
8.	Radio Path and Radio Network Planning Considerations	139
8.1	Radio Planning Terminology and Quality Targets	139
8.2	The Need for a 'Line-of-Sight'	140
8.3	Choosing the Ideal Locations for Radio Stations	141
8.4	The Fresnel Zone	142
8.5	Line-of-Sight Check (LOS-check)	146
8.6	LOS-Checks for Point-to-Point and Point-to-Multipoint Radio Systems	148
8.7	Increasing Link Range and Overcoming Obstacles on Point-to-Point Systems	149
8.8	Overcoming Coverage Problems and Shadows in Point-to-Multipoint Base Station Areas	151
8.9	Optimising the Capacity of Point-to-Multipoint Base Stations	153
8.10	The Significance of the Antenna Aperture Angle in Point-To-Multipoint Sector Antennas	154
8.11	The Fading Effects of Multipath Propagation	158
8.12	System Diversity and Link Hot-Standby Configurations (Protected Links)	159
8.13	Electromagnetic Interference and Electromagnetic Compatibility	160
8.14	Radio Planning Tools	160
9.	Radio Network Frequency Planning	161
9.1	Regulatory Restrictions on the Operation of Radio Systems	161
9.2	Interference between Radio Systems	166
9.3	Coordination Contour and CIR Contour Diagrams	167
9.4	Frequency Planning and Re-use in PTP Networks	169
9.5	Coordination Distance and Area	171
9.6	Radio Planning of PTP Links using Repeaters	173
9.7	Frequency Re-use in Point-to-Multipoint Radio Networks	174
9.8	Further Considerations for PMP Frequency Re-use Planners	179
9.9	Frequency Planning Considerations of ATPC	189
9.10	How Much Spectrum does a Radio Network Operator Need?	190
9.11	Guard Bands	191
<i>Part III</i>	<i>Applications, Network Integration and Management</i>	193
10.	Radio Applications and Network Integration	195
10.1	Choosing the Right Radio System Type for a Particular Application, Range and Bandwidth	195
10.2	Network Integration	201
10.3	Network Transmission Plan	201
10.4	Network Interfaces — To the Backbone Network and Customer Premises Equipment	215
10.5	Network Synchronisation	221

10.6 Network Services, Signalling and Protocols	223
10.7 Network Propagation Delays	223
10.8 Network Management and Monitoring	224
10.9 Service Accounting	224
10.10 Building Networks Robust against Failure	225
11. Wireless Local Loop (WLL)	227
11.1 The Use and Characteristics of Wireless Local Loop Systems	227
11.2 Access Network Interfaces	228
11.3 ETSI V5-Interfaces	229
11.4 Commercially Available Telephone and Basic Rate ISDN (BRI) Wireless Local Loop Systems	231
11.5 Mobile Telephone Networks used as a Means of Fixed Wireless Access	238
11.6 Iridium, Globalstar and the Evolution Towards the Universal Mobile Telephone Service (UMTS)	243
11.7 Shorthaul Microwave Radio for WLL	245
12. Backbone, Backhaul and High Capacity Access Radio Systems	247
12.1 Backbone Networks	247
12.2 History of the Synchronous Digital Hierarchy (SDH)	250
12.3 SONET (Synchronous Optical NETwork)	261
12.4 Backhaul in Mobile Telephone Networks	261
12.5 Point-to-Multipoint Backhaul	264
12.6 Point-to-Point for High Capacity Access	266
13. Data Networks and Radio	267
13.1 The Nature and Demands of Data Communication	267
13.2 Real Communication is 'Asymmetric' and 'Bursty'	268
13.3 Statistical Multiplexing by Means of a Combination of TDMA and ATM	268
13.4 Re-use of Upstream and Downstream Duplex Channels	269
13.5 Time Division Duplex (TDD)	273
13.6 Radio Systems Suited for Data Network Access	274
13.7 Third-generation Mobile Telephony	281
14. Broadband Wireless Access	283
14.1 The Different Philosophies for Spectrum Allocation	283
14.2 The Higher Frequency the Radio Band the Greater the Capacity!	284
14.3 MMDS (Multichannel Multipoint Distribution System)	287
14.4 LMDS (Local Multipoint Distribution Service)	288
14.5 LMCS (Local Multipoint Communications System)	290
14.6 The DAVIC (Digital Audio-Visual Council) Protocol	290
14.7 MVDS (Multipoint Video Distribution System)	292
14.8 Point-to-Multipoint	292
14.9 Broadband Point-to-Multipoint Equipment	293
14.10 BRAN (Broadband Radio Access Networks)	298
14.11 The Future — Squeezing More Capacity from Limited Spectrum	299

15. Radio System Installation	301
15.1 Site Acquisition, Survey and Preparation	301
15.2 Technical Site Survey (PMP Base Station or PTP Relay Station)	303
15.3 Necessary Permits	305
15.4 Radio Permits and Frequency Applications	305
15.5 The Positioning, Design and Installation of Steelwork or a Mast for Antenna Mounting	307
15.6 Peripheral Equipment and Site Preparation	316
15.7 Bringing into Service and Commissioning Radio Equipment	316
15.8 Project Organisation	317
15.9 Customer Site Installation	318
16. Operation and Management of Wireless Access Networks	319
16.1 Network Services to be Supported	319
16.2 Basic Operations Activities	320
16.3 Detailed Requirements of Operations Software Support Tools	321
Appendices	
Appendix 1 Radio Bands and Channel Rasters for Fixed Wireless Systems	337
Appendix 2 ETSI Radio Specifications for Fixed Wireless	343
Appendix 3 IEEE Publications and FCC Standards	347
Appendix 4 Waveguide Specifications	349
Appendix 5 Coaxial Cable Waveguides (RG-Nomenclature)	351
Appendix 6 Forward Error Correction Codes	353
Appendix 7 Wireless propagation, Frequency Re-use, Design and Operations	359
Appendix 8 World Climate Zones and their Precipitation Characteristics	373
Appendix 9 Rainfall Attenuation Prediction Model	379
Appendix 10 Safety, Environmental and EMC (Electromagnetic Compatibility) Standards Relevant to Fixed Wireless	381
Appendix 11 Radio Spectrum Charges for PTP and PMP System Operation	383
Appendix 12 Radio Regulations Agencies	385
Glossary of Terms	389
Bibliography	393
Index	395

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Martin Clark
Frankfurt, Germany
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Part I

Fundamentals of Fixed Wireless

Appendix 6

Forward Error Correction Codes

General

The basic principle of *Forward Error Correction (FEC)* is the addition of a number of *code* bits to a user signal to reduce the probability of a *bit error* arising during transmission of that user signal. For a user signal string of length k bits to be encoded we must find at least $2k$ separate and *orthogonal* codes—one distinct *codeword* for each possible bit combination in the original signal.

The *Hamming distance* (d) defines the difference in value of the individual codewords. Specifically, the Hamming distance is the minimum number of bit positions by which the individual codewords differ from one another. The larger the Hamming distance, the greater is the capability of the code to *detect* and *correct* errors in the presence of *noise* or *errors* introduced during transmission.

The number of errors that can be *corrected* is less than or equal to $(d - 1)/2$. The number of errors that can be *detected* is less than or equal to d .

There are five main types of forward error correction codes:

- *block codes* (including Hamming codes);
- *cyclic codes*;
- *BCH (Bose–Chaudhuri–Hocquenghem)* codes;
- *Reed–Solomon* codes;
- *Convolutional codes* (including *Viterbi codes*)

We briefly discuss the principles and mechanism of each of these types of codes.

Block Codes

Block codes break up the user data stream into a series of blocks of k bits in length. To each block, a code block of $(n - k)$ bits is added to make an n -bit *codeword*. The code is described by the notation (n, k) block code.

Thus, for example, a $(15, 4)$ code has 15 bit codewords, 11 bits of which are real coded user data, and four bits are *parity bits*. An example of a $(7, 3)$ code was given in Chapter 6.

In mathematical notation, the coding takes place as follows:

$$c = d[G]$$

where $\mathbf{c}$ is a vector representing the *codeword*, $\mathbf{d}$ is the vector of the user data, and $[\mathbf{G}]$ is the *generator matrix*.

The generator matrix is a matrix of dimensions k by n , made up of the *identity matrix* $[\mathbf{I}]$ and the *parity matrix* $[\mathbf{P}]$ (the matrix $[\mathbf{P}]$ identifies, for each of the parity bits, which bit positions in the user-data signal are used to calculate the parity):

$$[\mathbf{G}] = [\mathbf{I}\mathbf{P}]$$

An example of the various matrices and vectors for a simple (7, 3) block code might be as shown below. (Actually, these are the actual matrices relevant to the example we discussed in Chapter 6, but with the bits rearranged so that the data bits appear in the first three positions of the codeword and the parity bits thereafter):

$$\mathbf{d} = (0 \ 1 \ 1 \ 1)$$

$$\mathbf{G} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{bmatrix}$$

(The last three columns generate the parity bits. The rows of the column indicate which bits of the data are to be used for the calculation. The first parity bit will be based on bits 1, 2 and 4.)

$$\mathbf{c} = (0 \ 1 \ 1 \ 1 \ 1 \ 0 \ 0)$$

The matrix multiplication is performed *modulo 2*. The effect of this multiplication is to add $n-k$ parity bits to the end of the user data signal of k bits.

At the receiving end, the user data part of the signal (as received) is again subjected to the same parity calculation. The $n-k$ parity check result generated by the receiver is represented by the matrix formula $\mathbf{d}'[\mathbf{P}]$, where $\mathbf{d}'$ is that part of the received codeword representing the user data. The result should be equal to the received parity bit code $\mathbf{c}_p$. This can be determined by electronic hardware by a modulo 2 addition (which is equivalent to a modulo 2 subtraction). The result should be 0:

$$\mathbf{d}'[\mathbf{P}] + \mathbf{c}_p = [\mathbf{0}]$$

For our example above, let us assume that the data is received with a bit error at position three of the user data. This is equivalent to the second example of Figure 6.14:

$$\text{Received codeword} = \frac{(0 \ 1 \ 0 \ 1 \ 1 \ 0 \ 0)}{\mathbf{d}'} \begin{matrix} \mathbf{c}_p \\ 1 \ 0 \ 0 \end{matrix}$$

$$\mathbf{d}' = (0 \ 1 \ 0 \ 1)$$

$$\mathbf{P} = \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{pmatrix}$$

$$\mathbf{c}_p = (1 \ 0 \ 0)$$

$$\mathbf{d}'[\mathbf{P}] + \mathbf{c}_p = (0\ 1\ 0) + (1\ 0\ 0) = (1\ 1\ 0)$$

If the result is not 0 (as in our example above), then the values in the resulting vector can be used to determine the exact bit position of the error(s), and thus be used to correct them. Because of the rearrangement of the position of the bits, the correction values (3, 5, 6 and 7) will not, however, have the same meaning as in Chapter 6. Instead, these values will represent errors respectively at positions (1, 2, 3 and 4).

Our efforts to explain the process using matrix notation is because this aids the design of digital electronic circuitry.

Cyclic Codes

Cyclic codes are a special type of block code, in which each of the valid codewords are a simple lateral shift of one another. Thus, if one valid code of a (10, 3) cyclic code is:

$$\mathbf{c} = (1\ 0\ 1\ 0\ 1\ 0\ 0\ 1\ 0\ 0)$$

then

$$\mathbf{c} = (0\ 1\ 0\ 1\ 0\ 0\ 1\ 0\ 0\ 1)$$

is also a valid code, as is

$$\mathbf{c} = (1\ 0\ 1\ 0\ 0\ 1\ 0\ 0\ 1\ 0)$$

etc.

Using a cyclical structure of different codes enables us to correct larger blocks of errors than those possible with non-cyclic codes. A generator matrix with particular qualities is required to generate a *cyclic code*. In particular, the generator matrix for a cyclic code always has a value '1' as its last element (i.e. in the k th row of the n th column).

If we consider our example of the last section on block codes, we had a valid (7, 3) codeword of:

$$\mathbf{c} = (0\ 1\ 1\ 1\ 1\ 0\ 0)$$

(For the data value $\mathbf{d} = 0111$ the parity values were 100)

For this to be a cyclic code, all the other codes:

$$\begin{array}{ll} \mathbf{c} = (0\ 0\ 1\ 1\ 1\ 1\ 0) & \mathbf{c} = (1\ 1\ 0\ 0\ 0\ 1\ 1) \\ \mathbf{c} = (0\ 0\ 0\ 1\ 1\ 1\ 1) & \mathbf{c} = (1\ 1\ 1\ 0\ 0\ 0\ 1) \\ \mathbf{c} = (1\ 0\ 0\ 0\ 1\ 1\ 1) & \mathbf{c} = (1\ 1\ 1\ 1\ 0\ 0\ 0) \end{array}$$

must also be valid code words. But they are not. Another valid codeword is usually $\mathbf{c} = (0\ 0\ 0\ 0\ 0\ 0\ 0)$.

The data value (0 0 1 1), for example, yields the codeword (0 0 1 1 0 0 1), and not the allowed cyclic code (0 0 1 1 1 1 0).

The codeword $\mathbf{c} = (0\ 0\ 0\ 1\ 0\ 0\ 0)$ could also not be a valid (7, 3) cyclic codeword. Why? Because if it were, then $\mathbf{c} = (0\ 0\ 0\ 0\ 1\ 0\ 0)$ would also have to be a valid codeword. This is not possible, for a parity value of '1' is not possible for non-zero user data (the first four bits of the codeword). Not all block codes are cyclic codes!!

So, never mind the non-cyclic codes, how do we conceive the *generator matrix* of a cyclic code? By starting with the *generator polynomial* (the last row of the matrix).

For an (n, k) code we expect $n-k$ bits of user data and a k -bit parity code.

The *generator polynomial* has the form $x^{n-k} + ax^{n-k-1} + \dots + 1$ (a value is '1' or '0') and appears as the last row of the *generator matrix* in the form (for an example (7, 4) cyclic code):

$$\begin{bmatrix} x & x & x & x & x & x & x \\ x & x & x & x & x & x & x \\ 0 & 0 & 1 & 1 & 1 & 0 & 1 \end{bmatrix}$$

The first $n-k-1$ elements of the row must be zeros, and the last element must be a '1'. In other words, the generator polynomial is a polynomial of order k (first element x^k). The generator polynomial in this case is $x^4 + x^3 + x^2 + 1$. This determines the properties of the code, and defines one of the valid codewords, in this case (0 0 1 1 1 0 1). The full generator matrix is:

$$\begin{bmatrix} 1 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 & 1 \end{bmatrix}$$

The valid codewords are:

$$\begin{array}{ll} \mathbf{c} = (0 & 0 & 0 & 0 & 0 & 0 & 0) & \mathbf{c} = (1 & 0 & 0 & 1 & 1 & 1 & 0) \\ \mathbf{c} = (0 & 0 & 1 & 1 & 1 & 0 & 1) & \mathbf{c} = (1 & 0 & 1 & 0 & 0 & 1 & 1) \\ \mathbf{c} = (0 & 1 & 0 & 0 & 1 & 1 & 1) & \mathbf{c} = (1 & 1 & 0 & 1 & 0 & 0 & 1) \\ \mathbf{c} = (0 & 1 & 1 & 1 & 0 & 1 & 0) & \mathbf{c} = (1 & 1 & 1 & 0 & 1 & 0 & 0) \end{array}$$

BCH Codes (Bose–Chaudhuri–Hocquenghem)

BCH-Codes are cyclic codes designed to provide for multiple error correction. The most commonly used BCH-codes are Reed–Solomon codes.

Reed–Solomon Codes

When talking about *Reed–Solomon* codes, it is common to talk about the coding of *symbols*. In many data applications, for example full *bytes* or *octets* (of 8 bits each) are used to represent a given alphanumeric *symbol*. For 8 bits there are $q = 256$ ($q = 2^8$) possible different symbols (values). Thus, we must have 256 different codewords available.

A Reed–Solomon code is a *block code* and *cyclic code* of type (n, k) as we previously discussed. The input number of data bits is $n-k$ and the codeword symbols are n bits in length. It is usual that the value of n be restricted to no more than $q-1$ (i.e. $n < q$). In our example, this means a maximum value of $n = 255$.

The code is often quoted in terms of its byte size. A typical code might be (64, 24), thus 40 bytes of data are protected with 24 bytes of code (64 bytes total). Each codeword would be $64 \times 8 = 512$ bytes long. However, of the 2^{512} combinations available, only 64^{24} combinations (i.e. $2^{6 \times 24} = 2^{144}$) combinations would actually be used. This enables up to $24/2 = 12$ symbol errors to be corrected.

Convolutional Codes

Convolutional codes work on a shift register basis. A string of consecutive bits of the input user data stream (of K bits in length, where K is the *constraint length* of the code). This string of bits are subject to a series of *modulo 2* summation actions (in effect, parity checks). The number of summation codes to which the K -bit sequence is subjected is denoted by v . The coding which results from a $1/v$ coder using v different code summations is called a $1/v$ *convolutional code*.

Figure A6.1 illustrates $\frac{1}{2}$ convolutional coder with a *constraint length* of $K=3$.

The two codes being used (in alternation to produce the output bitstream) are:

$$c_1 = d_0 + d_1 + d_2$$

$$c_2 = d_0 + d_2$$

Table A6.1 illustrates the output from this coder.

Convolutional codes of *constraint length* $K=7$ are often used, with a codeword length of 28 or 35 bits ($v=4$ or 5).

The *shift register* nature of convolutional codes makes them very easy to implement in a digital electronic circuit design. In addition, the complete codeword does not have to have been received before decoding can commence. This minimises the signal delays caused during transmission.

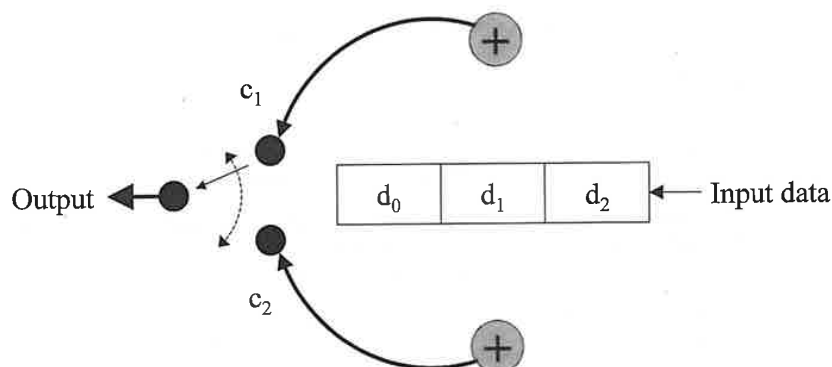


Figure A6.1 $\frac{1}{2}$ convolutional coder with *constraint length* $K=3$

Table A6.1 Convolutional code and output

Time interval	1	2	3	4	5	6	7	8
Input bitstream	0	1	1	0	1	0	0	1
Bits in register ($d_0d_1d_2$)	000	000	011	110	101	010	100	001
Output variable	c_1 c_2	c_1 c_2	c_1 c_2	c_1 c_2	c_1 c_2	c_1 c_2	c_1 c_2	c_1 c_2
Output bitstream	0 0	1 1	0 1	0 1	0 0	1 0	1 1	1 1

Viterbi Codes

Viterbi codes are a particular type of convolutional code. In particular, Viterbi determined a methodology for the correct decoding (or rather the most likely correct interpretation or *maximum likelihood* decoding) of incorrectly received codewords.

Coding Gain

One talks of the *coding gain* achieved by using *Forward Error Correction (FEC)*. This gain is the effective improvement in the *receiver sensitivity* of the receiver (we defined this term in Chapter 6). The improvement in sensitivity results from the correction of some of the errors (resulting in an improvement in the signal quality) at a given received signal power. Typical coding gains due to FEC are around 3 to 6 dB.