In this chapter we deal with the mechanics of the switching process, describing the sequence of functions necessary to establish connections across a telecommunications network. We shall cover the principles of circuit switching (as would be used in voice or circuit data networks) as well as the statistical multiplexing switching techniques of packet and cell switching. In addition, we describe in outline some of the better known types of switch technology.

6.1 CIRCUIT-SWITCHED EXCHANGES

In circuit-switched networks a physical path or circuit must exist for the duration of a call between its point of origin and its destination, and three particular attributes are needed in all circuit-switched exchanges.

- First, the ability not only to establish and maintain (or hold) a physical connection between the caller and the called party for the duration of the call but also to disconnect (clear) it afterwards.
- Second, the ability to connect any circuit carrying an incoming call (incoming circuit) to one of a multitude of other (outgoing) circuits. Particularly important is the ability to select different outgoing circuits when subsequent calls are made from the same incoming circuit. During the set-up period of each call the exchange must determine which outgoing circuit is required usually by extracting it from the dialled number. This makes it possible to put through calls to a number of other network users.
- Third, the ability to prevent new calls intruding into circuits which are already in use. To avoid this the new call must either be diverted to an alternative circuit, or it must temporarily be denied access, in which case the caller will hear a busy or engaged tone or the data user will receive an equivalent message or signal.

Exchanges are usually designed as an array or matrix of switched crosspoints as illustrated in Figure 6.1.
The switch matrix illustrated in Figure 6.1 has five incoming circuits, five outgoing circuits and 25 switch crosspoints which may either be made or idle at any one time. Any of the incoming circuits, A to E, may therefore be interconnected to any of the outgoing circuits, 1 to 5, but at any particular instant no incoming circuit should be connected to more than one outgoing circuit, because each caller can only speak with one party at a time. In Figure 6.1, incoming circuit A is shown as connected to outgoing circuit 2, and simultaneously C is connected to 1, D to 4 and E to 3. Meanwhile, circuits B and 5 are idle. Therefore, at the moment illustrated, four calls are in progress. Any number up to five calls may be in progress, depending on demand at that time, and on whether the called customers are free or not. Let us assume, for example, that only a few moments before the moment illustrated, customer B had attempted to make a call to customer 3 (by dialling the appropriate number) only to find 3's line engaged. Any telephone user will recognise B's circumstance. However, only a moment later, customer E might cease conversation with customer 3, and instantly make a call to customer 5. If B then chances to pick up the phone again and redial customer 3's telephone number, the call will complete because the line to C is no longer busy. Figure 6.2 shows the new switchpoint

![Figure 6.1](image1.png)

**Figure 6.1** A basic switch matrix at a typical instant in time

![Figure 6.2](image2.png)

**Figure 6.2** The same switch matrix a few moments later
configuration at this subsequent point in time, when five calls (the maximum for this switch) are simultaneously in progress.

At any one time, between nought and five of the twenty-five crosspoints may be in use, but never can an incoming circuit be connected to more than one outgoing circuit, nor any outgoing circuit be connected to more than one incoming circuit.

What exactly do we mean when we say a connection is made? In previous chapters on line transmission methods we concluded that a basic circuit needs at least two wires, and that a long distance one is best configured with four wires (a transmit and a receive pair). How are all these wires connected by the switch, and how exactly is intrusion prevented?

The answer to the first question is that each of the two (or four) wires of the connection is switched separately, but in an array similar to that in Figure 6.2. Thus a number of switch array ‘layers’ could be conceived, all switching in unison as shown in Figure 6.3, which illustrates the general form of a four-wire switch.

Each layer of the switch shown in Figure 6.3 is switching one wire of the four. Each of the four layers switches at the same time, using corresponding crosspoints so that all of the four wires comprising any given incoming circuit are connected to all the corresponding wires of the selected outgoing circuit (note that in Figure 6.3, circuit A is connected to circuit 5).

Additionally, in Figure 6.3 you will see that the fifth or so-called P-wire has also been switched through. The use of such an ‘extra’ wire is one way of designing switches to prevent call intrusion. Usually this method is used in an electro-mechanical exchange and it works as follows.

When any of circuits A to E are idle, there is an electrical voltage on their corresponding P-wires. When any of the callers A to E initiates a new call, the voltage on the P-wire is dropped to earth (zero volts). When the call is switched through the matrix to any of the outgoing circuits 1 to 5, the P-wire of that circuit will also be earthed as a result of being connected to the P-wire of the incoming circuit. When the call is over, the caller replaces the handset. This causes a voltage to be re-applied to

![Figure 6.3 Switching a four-wire connection](image-url)
the P-wire, to which the switch matrix responds by clearing the connection. Intrusion is prevented by prohibiting connection of circuits to others for which the P-wire is already in an earthed (i.e. busy) condition. In this way, the earth on the P-wire is used as a marker to distinguish lines in use.

The P-wire also provides a useful method of circuit holding, and for initiation of circuit clearing. To this end the switch is designed to maintain (or hold) the connection so long as the P-wire is earthed. As soon as the caller replaces the handset, the P-wire is reset to a non-zero electrical voltage, and the switch responds by clearing the connection (i.e. releasing the switch point).

In modern computer-controlled (stored program control (SPC)) exchanges call intrusion is prevented, and the job of holding the circuit is carried out by means of the exchange processor's electronic 'knowledge' of the circuits in use. P-wires are thus becoming obsolete.

To return to the example in Figures 6.1 and 6.2, what if party A wishes to call party E? Our diagrams show A and E as only able to make outgoing calls through the switch, so how can they be connected together? The answer lies in providing one or both circuits with access to both incoming and outgoing sides of the exchange, and it is done by commoning (i.e. wiring together) circuits 1 and A, 2 and B, 3 and C, 4 and D, 5 and E, as shown in Figure 6.4. (Incidentally, in the example shown in Figure 6.4 as well as in other diagrams in the remainder of the chapter, it is necessary to duplicate the layers for each of the two or four wires of the connection, as already explained in Figure 6.3. For simplicity, however, the diagrams only illustrate one of the layers).

---

**Figure 6.4** A simple small local exchange
In Figure 6.4, any of the customers A to E may either make calls to, or receive calls from, any of the other four customers. The maximum number of simultaneous calls now possible across the matrix is only two, as compared with the five possible in Figure 6.2. This is because two calls are sufficient to engage four of the five available lines. One line must therefore always be idle.

A switch matrix designed in the manner illustrated in Figure 6.4 would serve well in a small exchange with only a few customers, such as an office private branch exchange (PBX) or a small local exchange (termed central office or end office in North America) in a public telephone network. The exchange illustrated in Figure 6.4 is actually a full availability and non-blocking system. Fully available means that any line may be connected to any other; non-blocking indicates that so long as the destination line is free a connection path can be established across the switch matrix regardless of what other connections are already established. These terms will be more fully explained later in the chapter and we shall also discover some of the economies that may be made in larger exchanges, by introducing limited availability.

First, let us consider how the isolated system of Figure 6.4 can be connected to other similar systems in order to give more widespread access to other local exchanges, say, or to trunk and international exchanges. Figure 6.5 illustrates how this is done. It shows how some circuits, which are designated as incoming or outgoing junctions, connect the exchange to other exchanges in the network. Such inter-exchange circuits allow connections to be made to customers on other exchanges.

Networks are built up by ensuring that each exchange has at least some junction, tandem or trunk circuits to other exchanges. The exchanges need not be fully interconnected, however; connections can also be made between remote exchanges by the use of transit (also called tandem) routes via third exchanges, as shown in Figure 6.6. Junction and trunk circuits are always provided in multiple numbers. This means that if one particular circuit is already in use between two exchanges, a number of equally suitable alternative circuits (interconnecting the same exchanges) could be used instead. Figure 6.6 shows four circuits interconnecting exchanges P and Q; two each for incoming and outgoing directions of traffic. The consequence is that when circuit 1 from exchange P to exchange Q is already busy, circuit 2 may be used to establish another call. Only when both circuits are busy need calls be failed, and callers given the busy tone.

Each of the exchanges shown in the networks of Figures 6.5 and 6.6 must have its switch matrix and circuit-to-exchange connections configured as illustrated in Figure 6.7.

![Figure 6.5 Junction connection to other exchanges](image-url-here)
Figure 6.6 Typical networking arrangements

Figure 6.7 Local exchange configuration

Figure 6.7 shows how the local customers' lines are connected to both incoming and outgoing sides of the switch matrix, and how in addition a number of uni-directional (i.e. single direction of traffic) incoming and outgoing junctions are connected.

The junctions of Figure 6.7 could have been designed to be bothway junctions. In this case, like the customers' lines illustrated in Figure 6.4, they would need access to both incoming and outgoing sides of the switch matrix. In some circumstances this can be an inefficient use of the available switch ports, because it may reduce the number of calls that the switch can carry at any given time. (Remember that the matrix in Figure 6.4 may only carry a maximum of two calls at any time, while the same size matrix in Figure 6.1 could carry five calls).

6.2 CALL BLOCKING WITHIN THE SWITCH MATRIX

Telecommunications networks which are required to have very low call blocking probabilities need to be designed with excess equipment capacity over and above that needed to carry the average call load. Indeed, to achieve zero call blocking, we would need to provide a network of an infinite size. This would guarantee enough capacity
even in the unlikely event of everyone wanting to use the network at once. However, because an infinitely sized network is impractical, telecommunications systems are normally designed to be incapable of carrying the last very small fraction of traffic. Switching matrices are similarly designed to lose a small fraction of calls as the result of internal switchpoint congestion.

In the case of switch matrices we refer to the designed lost fraction of calls as the switch blocking coefficient. This coefficient exactly equates to the grade-of-service that we shall define in Chapter 30, and the dimensioning method is exactly the same. Thus a switch matrix with a blocking coefficient of 0.001 is designed to be incapable of completing 1 call in 1000. That one call will be lost as a direct consequence of switch matrix congestion. By comparison, a non-blocking switch is designed in such a way that no calls fail due to internal congestion.

How does switch blocking come about anyway, and how can costs be cut by designing switches with relatively large switch blocking coefficients? There are two methods of economizing on hardware, both of which inflict some degree of call blocking due to switch matrix congestion. They rely either on

- limiting circuit availability, or on
- employing fan-in, fan-out switch architecture.

and they are described separately below.

6.3 FULL AND LIMITED AVAILABILITY

All switches fall into one of two classes:

- full availability switches, or
- limited (or partial) availability switches

The difference between the two lies in the internal architecture of the switch. The term availability, in this context, is used to describe the number of the circuits in a given outgoing route which are available to any individual incoming circuit. As an example, Figure 6.8 illustrates a simple network in which five customers, A to E, are connected to an exchange P, which, in turn, has five junction circuits to exchange Q. However, Figure 6.8 is not drawn in sufficient detail to show the availability of circuits within the group of junction circuits joining P and Q, because the architecture of the switch matrix itself is not shown.

Figures 6.9 and 6.10 illustrate two of many possible switch matrix architectures for the exchange P which was shown topologically in Figure 6.8. In Figure 6.9, all the outgoing trunk circuits from P (numbered 1 to 5) may be accessed by any of the customers lines, A to E. This is the fully available configuration, as all outgoing circuits are available to all the incoming circuits.

By contrast, in Figure 6.10 each of the customers may only access four of the five outgoing circuits. Not all of them get through to the same four, though. Customer A
Figure 6.8 Customers A to E on exchange P, which has five circuits to exchange Q

may access circuits 1, 2, 3, 4, customer B circuits 1, 2, 3, 5, customer C circuits 1, 2, 4, 5, customer D circuits 1, 3, 4, 5 and customer E circuits 2, 3, 4, 5. Figure 6.10 shows only one of a number of possible permutations (called gradings) in which the outgoing circuits could be made available to the incoming ones. Figure 6.10 therefore illustrates one particular limited availability grading. The availability of the grading shown is 4, as only a maximum of four outgoing circuits (within the outgoing route PQ) are available to any individual incoming circuit. This despite the fact that more than four circuits exist within the route as a whole. In this example the total route size PQ is five circuits.

Note in Figure 6.10 how the total number of switch crosspoints is only 20 compared with the 25 that were required in Figure 6.9. This may give the advantage of reducing the cost of the exchange, particularly if the switch matrix hardware is expensive. On the other hand it may be an unfortunate limitation of the hardware design that only four outgoing ports are possible per incoming circuit. As we will find later in this chapter, electromechanical switches are often not configurable as full availability switches because of the way they are made.

The disadvantage of limited availability switches is that more calls are likely to fail through internal congestion than with an equivalent full availability switch. The difference between the two is plain in Figures 6.9 and 6.10. In Figure 6.10, when circuits 1 to 4 are busy but circuit 5 is not, call attempts made on line A are failed, whereas the same

\[
\begin{array}{ccccc}
1 & 2 & 3 & 4 & 5 \\
A & \rightarrow & 0 & 0 & 0 & 0 & 0 \\
B & \rightarrow & 0 & 0 & 0 & 0 & 0 \\
C & \rightarrow & 0 & 0 & 0 & 0 & 0 \\
D & \rightarrow & 0 & 0 & 0 & 0 & 0 \\
E & \rightarrow & 0 & 0 & 0 & 0 & 0 \\
\end{array}
\]

Figure 6.9 Switch matrix of exchange P configured as ‘fully available’
attempts made on the configuration in Figure 6.9 will succeed, hence the lower switch blocking of the latter. Similarly, B cannot reach circuits 4, nor C circuit 3, D circuit 2 or E circuit 1.

In the past a whole statistical science grew up in order to minimize the grade of service impairments encountered in limited availability systems. It was based on the study of grading which involves determining the slip-pattern of wiring (for example see Figure 6.10) in which optimum use of the limited available circuits is achieved. The resultant grading chart is often diagramatically represented in a form similar to that shown in Figure 6.11.

Figure 6.11 illustrates the grading chart of a number of selectors (switching mechanisms) sharing a common group of outgoing circuits to the same destination (e.g. a distant exchange). In total, 65 outgoing circuits are available in the grading, but of these, each individual incoming circuit (and its corresponding selector) can only be

Figure 6.10 Switch matrix of exchange P configured as 'limited availability' (4)

Figure 6.11 A 20-availability grading
connected to 20 of the 65. In other words, each selector (and therefore its corresponding incoming circuit) has a limited availability of 20. Thus the top horizontal row of 20 circuits shown on the grading chart of Figure 6.11 are the outlets available to a particular incoming circuit. The second row, meanwhile, represents the 20 outlets available to a different incoming circuit.

The action of a particular incoming circuit's selector mechanism is to scan across its own part of the grading (i.e. its horizontal row) from left to right, and to select the first available free circuit nearest the left-hand side. Other selectors similarly scan their rows of the grading to select free outgoing circuits. This means that outgoing circuits towards the left-hand side of the grading chart are generally more heavily used than those on the right. To counteract this effect, the right hand outlets of the grading (i.e. the later choices) are combined as doubles, trebles, quads, fives and tens, etc. This means that the same outgoing circuits are accessible from more than one selector, and thus incoming circuit. This helps to boost the average traffic carried by outgoing circuits in the 'later part' of the grading and so create even loading. The science of grading was particularly prevalent during the days of electromechanical exchange predominance, and different types of grading emerged, named after their inventors (e.g. the O'Dell grading).

In the diagram of Figure 6.11 you will see that apparently 10 incoming circuits (the number of horizontal rows) have access to a far greater number (65) of outgoing trunks circuits, all to the same destination exchange. Absurd you might think, and you would be right. There is no point in having more outlets to the same destination than the incoming demand could ever need. The explanation is that in practice the grading horizontal reflects identical wiring of ten or twenty selectors making up a whole shelf. In our case, then, 100 (10 × 10) or 200 (20 × 10) incoming circuits are vying for 65 outgoing trunks. You will agree that this is much more plausible. The reason that the grading is simplified in this way is that it is much easier to design and wire a 10 × 20 grading and duplicate it than it is to create a 100 × 20 or 200 × 20 grading.

In our example, if 20 or fewer circuits would have sufficed to meet the traffic demand to the destination then the grading work is much easier. In this case, all the selector outlets of Figure 6.11 may be commoned and full availability of outgoing circuits is possible, each incoming circuit capable of accessing each outlet.

Limited availability switches are nowadays becoming less common, as technology increasingly enhances the sophistication and reduces the cost of modern exchanges, thereby removing many of the hardware constraints and extra costs associated with limited availability switch design. Among older exchange technologies, limited availability was a common hardware constraint. Typically, Strowger type exchanges (described later in this chapter) were either 10-, 20- or 24- availability. In other words each incoming circuit had access only to a maximum of either 10, 20 or 24 circuits.

6.4 FAN-IN–FAN-OUT SWITCH ARCHITECTURE

In Figure 6.4 we developed a simple exchange, suitable on a small scale to be a fully-available and non-blocking switching mechanism for full interconnectivity between five customers. It was achieved with a switch matrix of 25 crosspoints. Earlier in the chapter
we suggested that economies of scale could be made within larger switches. The main technique for achieving these economies is the adoption of a fan-in–fan-out switch architecture.

Consider a much larger equivalent of the exchange illustrated in Figure 6.4. A typical local exchange, for example, might have 10,000 customer lines plus a number of junction circuits, so that in using a configuration like Figure 6.4, a matrix of around 10,000 \( \times \) 10,000 switch crosspoints would be required. Bearing in mind that a typical residential customer might only contribute on average 0.5 calls to the busy hour traffic, and that each call has an average duration of 0.1 hours (6 minutes), then the likely maximum number of these switchpoints that will be in use at a given time is only around 10,000 \( \times \) 0.05, or 500. The conclusion is that a similar arrangement to Figure 6.4 is rather inefficient on this much larger scale.

Let us instead set a target maximum switch blocking of 0.0005. In other words, we intend that a small fraction (0.05%) of calls be lost as the result of internal switch congestion. This is a typical design value and such target switch blocking values can be met by using the fan-in–fan-out architecture illustrated in Figure 6.12.

Note how the total number of switchpoints needed has been reduced by breaking the switch matrix into fan-in and fan-out parts. 561 connections join the two parts, the significance of the value 561 being that this is the number of circuits theoretically predicted to carry 500 simultaneous calls, with a blocking probability of 0.05% (see Chapter 30). The switch is now limited to a maximum carrying capacity of 561 simultaneous calls, but the benefit is that the total number of switchpoints required is only \(2 \times 561 \times 10,000\) or around 10 millions (a tenth of the number required by the configuration like that of Figure 6.4). This provides the potential for savings in the cost of switch hardware.
In our example it is intended that the internal blocking should never exceed 0.05% of calls failed due to internal switch congestion. In practice the actual switch blocking depends on the actual offered traffic, and it may be slightly higher or lower than this nominal value.

6.5 SWITCH HARDWARE TYPES

We have dealt with the general principles of exchange switching and the need for a number of incoming lines to be able to be connected to a range of outgoing lines, using a matrix of switched crosspoints. We now go on to discuss the different ways in which the matrix can be achieved in practice, and describe four individual switch types. In chronological order these are:

- Strowger (or step-by-step) switching
- crossbar switching
- reed relay switching
- digital switching

A number of other types, Rotary, 500-point, panel and X-Y switching systems have been developed over the years. They are not discussed in detail here.

6.6 STROWGER SWITCHING

Strowger switches were the first widely used type of automatic exchange systems. They were developed by and named after an American undertaker who was keen to prevent human operators transferring calls to his competitors. His patent was filed on 12 March 1889.

Strowger exchanges are a marvel of engineering ingenuity, using precisely controlled mechanical motion to make electrical connections and, though now largely obsolete, they provide a valuable insight into the switching functions necessary in a telephone network, and an understanding of some of the historical reasons for modern telephone network functions and structures. The combination of electrical and mechanical components used in Strowger switching leads to the much-used expression electro-mechanical switching.

The switching components of Strowger exchanges are usually referred to as selectors, and they work in a manner which is marvellously easy to understand. In its simplest form, a selector consists of a moving set of contacting arms (known as a wiper assembly) which moves over another fixed set of switch contacts known as the contact bank. The act of switching consists of moving (or stepping) the contactor arm over each contact in turn until the desired contact is reached. Two main types of Strowger (or step-by-step) selectors are used in most exchanges of this type. They are called uniselectors and two-motion selectors.
A uniselector is a type of selector in which the wiper assembly rotates in one plane only, about a central axis. The contactors move along the arc of a circle, on which the fixed contact bank is arranged. Figure 6.13 illustrates the principle. A single incoming circuit is connected to the uniselector's contactor on the wiper assembly, and 25 possibly outgoing circuits are connected, one to each of the individual contacts making up the contact bank. The first contact in the bank is not connected to any outgoing circuit, but serves as the rest position for the wiper arm during the idle period between calls, thus in practice only 24 outlets are available.

When a call comes in on the incoming circuit, indicated by a loop (say, because the customer has picked his phone up), the uniselector automatically selects a free outgoing connection to a first selector. The first selector is a Strowger 2-motion selector which initially returns the dial tone to the caller and subsequently responds to the first dialled digit. We shall discuss the mechanism of 2-motion selectors shortly.

Uniselectors consist of a number of rows (or planes) of bank contacts, as the photograph in Figure 6.14 illustrates. The use of a number of planes allows all the contacts necessary for two, three or four wire and P-wire switching to be carried out simultaneously.

How do we cope with more than one incoming circuit? One answer is to provide a uniselector corresponding to each individual callers line. The outlets of these uniselectors can then be graded as we have seen to provide access to a suitable number of first selectors sufficient to meet traffic demand. A simple arrangement of this type is shown in Figure 6.15(a). However, unless the traffic on the incoming circuit is quite heavy then this arrangement is relatively inefficient and uneconomic, requiring a large number of uniselectors which see little use. For this reason it is normal to provide also a hunter or linefinder. This is a second uniselector, wired back-to-back with the first as shown in Figure 6.15(b). The linefinder (or hunter) is used to enable the first uniselector to be shared between a number of incoming lines. A number of linefinders (sufficient to meet customers traffic demand) are graded together, giving each individual line a number to choose from (Figure 6.15(c)).

![Figure 6.13 A simple uniselector](image-url)
Figure 6.14  Strowger uniselector. The wipers move in the arc of a circle around 25 outlet contacts, stopping at a free outlet. Uniselectors are typically used on the customer side of an exchange, helping to find free exchange equipment to handle the call.

Different selectors in the same grading are prevented from simultaneously choosing the same outgoing circuit by the action of the P-wire, as we saw earlier in the chapter. It is also the P-wire that invokes the release of the selectors at the end of a call, whereupon a spring or other mechanical action returns the wiper assembly to the rest or home position.

The most common type of selector found in Strowger exchanges is the two-motion selector. These are the type capable of responding to dialled digits. The wipers of a two-motion selector can, as the name implies, be moved in two planes. The first motion is linear, up-and-down between the ten planes (or levels) of bank contacts under dialled digit control. This is followed by a circular rotation into the bank itself. The second motion can be an automatic motion, scanning across the grading to find a free connection to a subsequent two-motion selector to analyse the next digit. Alternatively, if the two-motion selector is a final selector, then the selector analyses both the final two digits of the called customers number. In this case the rotary motion of the selector is controlled by a dialled digit.
Each contact bank plane in a two-motion selector appears as an arch shaped layer or level with a number of sets of equally spaced contacts in each bank. The appearance of the selector contact bank is thus somewhat akin to a portion of a cylinder, as Figure 6.16 shows.

In practice the cylindrical bank of a two-motion selector needs to be duplicated to allow each of the wires of a connection (two-wire plus P-wire, etc.) to be connected
Figure 6.16 The principle of the Strowger two-motion selector. An illustration from an old manuscript, showing the basic action of the two-motion selector. Pulsing the VM relays initially steps the wiper in the vertical plane. RM relay pulses then move the wiper an appropriate number of contacts in the horizontal plane. (Courtesy of BT Archives)

simultaneously, so that an actual two motion selector looks a little more complicated, as the photograph Figure 6.17 reveals.

Having heard the dial tone returned from the first selector (when it is ready), the caller dials the called number. This is indicated to the exchange by a train of electrical loop-disconnect ('off–on') pulses on the incoming line itself. These are the pulses which activate first, second or subsequent two-motion selectors accordingly. The number of ‘off–on’ pulses used to represent a particular digit corresponds to the value of the digit
Figure 6.17  Strowger two-motion selector. This one is actually a final selector, used in the British Post Office network. (Courtesy of BT Archives)

dialled. Thus one pulse is the digit value 1, two pulses equals value 2 etc. The digit value 0 is represented by ten pulses. This simple form of signalling is called loop disconnect or LD signalling; it was described in Chapter 2. Each pulse steps the selector upwards in the vertical plane by one level. The gap between dialled trains of pulses (the inter-digit pause) indicates the end of the train and so marks the end of the stepping sequence. When a two-motion selector detects the gap between dialled digits then the rotary action of the selector commences automatically, moving the wiper into the bank to find
a free connection. Alternatively, in the case of a final selector, the *inter-digit pause* is used by the selector to ready itself for receiving a second dialled digit to control its rotary motion.

Digressing for a moment, it is worth noting that a Strowger two-motion selector has a limited availability of 10 (or sometimes 20). The constraint arises because the selector may only automatically scan the horizontal levels of the bank and on each a maximum of 10 (or 20) outlets may be accommodated.

Apart from being ideal for the direct stepping of two-motion Strowger selectors, another benefit of *loop disconnect* signalling is the ease with which pulses may be generated by a dial telephone. Figure 6.18 shows a dial telephone and how the pulses of loop disconnect signalling are created by a rotating cam attached to the telephone dial. As the dial is turned, the cam operates a set of contacts which connect and disconnect the circuit. Depending on how far the dial is turned, a number of pulses are generated. A longer period of electrical current ‘on’ separates the bursts corresponding to consecutive digits of the number. This longer on-period is called the *inter-digit pause* and is generated by an initial wide tooth on the rotating cam, as shown in Figure 6.18.

Actual Strowger exchanges comprise both *uniselector* and *two-motion selector* types. Figure 6.19 shows an example of a permutation of uniselectors and two-motion selectors to support up to 1000 customers on a three-digit numbering scheme. The uniselector finds a *free first selector*, which analyses the first dialled digit and then finds a *free final selector* in the correct range (corresponding to the first dialled digit). The final selector provides the final connection to the customer.

For networks consisting of more than one exchange it is clear that the same destination customer will not always be reached using the same route from the calling customer, because the starting place is not always the same. All routes, however, will comprise a number of switching stages, located in the various exchanges. These need to be fed with trains of digit impulses to operate. As the path is not common, then each caller will either have to dial a different string of digits, or else each exchange will have to be capable of *translating* a common dialled string into the string necessary to activate the selectors on the route needed from that particular exchange. In the latter case, a
so-called common or linked numbering scheme, a register/translator is needed to store the dialled digits and translate (or convert) them into the string of routing digits which are needed to step the selectors as previously described. The function of the register and the technique of number translation are both described more fully in the next chapter.
Finally, let us close our discussion of Strowger switching by explaining briefly why the phenomenon of limited availability arises. It comes about because each selector is limited in the number of bank contacts. On a uniselector this is typically 24. On a two-motion selector it is usually only 10 or 20. Thus no matter how many circuits make up the route in total, each incoming circuit may have access only to a limited number of them (24, 10 or 20 in the examples given above).

The major drawback of Strowger switching was the relatively large amount of space that it takes up, the relatively high electrical power needed for busy-hour operation, and the labour-intensive demands of maintaining it. The mechanical parts are highly prone to wear, and the electrical contacts are very sensitive to damage and dirt. As a result Strowger switching is nowadays largely obsolete, though some Strowger exchanges still operate in remote areas and may well remain in those lacking the capital to replace them.

6.7 CROSSBAR SWITCHING

Crossbar technology emerged in the 1940s and was partly, though not wholly, responsible for a change in equipment usage away from Strowger and other similar step-by-step exchange types. Crossbar switching offered the advantage of reduced maintenance and accommodation requirements, but was sometimes more expensive than Strowger for large and complex exchange applications.

As early as 1926 the first public crossbar exchange opened in Sweden. It worked in a step-by-step, digit-by-digit, manner which was too unwieldy for exchanges exceeding 2000 lines. It was not until the 1940s that crossbar systems became more common, following development in America of a system employing marker control. This became by far the most common type of crossbar exchange and it is the type described here.

The technique of crossbar switching is relatively easy to understand, because the switch matrix is immediately apparent from the physical structure of the components.

![Figure 6.21](image-url)  
Figure 6.21  Crossbar switching matrix. A typical basic crossbar matrix. This one comprises ten armatures and bridge magnets, six select bars and twelve select magnets. (Courtesy of British Telecom)
As the photograph in Figure 6.21 shows, the switch looks like a matrix, consisting of ordered vertical and horizontal members.

The operation of the crossbar switch is most readily understood by considering the action of two adjacent crosspoints. Figure 6.22 shows a single crosspoint of a crossbar assembly. The adjacent crosspoint of interest is a mirror image of the one shown immediately below it.

The crosspoint shown in Figure 6.22 is capable of simultaneous switching of three inlet wires to three outlet wires. The three inlet wires (a pair plus a P-wire) are connected to three fixed bridge common contacts and the three outlet wires are connected to three moveable outlet spring contacts. The three outlet spring contacts are joined together by a piece of insulating material, which also connects the outlet springs to the lifting spring. Thus when the lifting spring is moved to the right of the diagram the outlet springs are all simultaneously pushed into contact with the bridge common, so completing the connection. (As an aside, more wires can also be switched simultaneously, by adding more outlet springs and bridge commons).

Figure 6.22  Operation of a crossbar switch
The lifting spring is actuated by the action of the select finger and the bridge armature. The select finger is really a thin piece of wire, connected to the select bar by a small spring, and this gives the select finger a small amount of flexibility. The select magnets are electromagnets, activated by passing an electric current through their coils. Not more than one of the select magnets is used at any one time. To activate the crosspoint shown in Figure 6.22, select magnet 2 must be operated. This has the effect of tilting the select bar, and so moving the select finger into the position marked by the dashed line on our diagram. At this point the bridge magnet is activated. This in turn pivots the bridge armature, with the effect of trapping the select finger onto the lifting spring, so moving the lifting spring towards the right of the diagram, and making contact between the outlet springs and the bridge commons. The connection is now complete. The bridge magnet must remain held as long as the connection is required, so trapping the select finger for the entire call. The select magnet, however, may be released once the connection has been made. The slight flexibility in the select finger permits it to remain trapped under the bridge armature, even when the select magnet is released.

At the end of the call, the bridge magnet is released, and the select finger springs back to its normal position.

By a similar mechanism, another set of outlet spring contacts (beneath the set illustrated) can be connected to the same inlet bridge commons (inlet circuit). In fact, this is the function of select magnet 1. The contacts are arranged in a mirror image beneath those of our illustration, and work in precisely the same way except that they use select magnet 1 instead of select magnet 2. Thus select magnet 1 selects one outlet circuit while select magnet 2 selects the other. It does not matter that there is only one select finger available, as we would not wish to connect the inlet to both outlets at the same time anyway.

Figure 6.23 illustrates a larger portion of a crossbar switch, showing three bridge magnets and armatures and two select bars. The form of the overall switch matrix is now apparent. To activate any particular crosspoint of the matrix one of the select magnets must be activated (according to the desired outlet circuit required) and then the appropriate bridge magnet is also activated, to connect the desired inlet circuit.

![Figure 6.23 A crossbar matrix](image-url)
Crossbar switch assemblies usually consist of 10 bridge armatures and 6 select bars, requiring 10 bridge magnets and 12 select magnets. (Note: some manufacturers of crossbar switches used more armatures and bridge magnets than discussed here. The principle, however, is the same.) Used in its most straightforward manner, therefore, a single crossbar switch assembly can be used for 10 inlets and 12 outlets. By combining a number of these assemblies a much bigger matrix can be built up.

The limited availability of 12 outlets from the basic assembly can raise problems, as we saw earlier in the chapter. So let us consider how we could improve things to allow 20 outlets. A single bridge of a 20 outlet switch is shown in Figure 6.24. Note that there are now six bridge commons and corresponding sets of outlet springs instead of only three. Notice also how the top two magnets have been labelled as auxiliary magnets instead of select magnets.

Figure 6.24 Twenty-outlet crossbar switch
In the assembly shown in Figure 6.24 each crosspoint is made by activating three magnets: one of the auxiliary magnets, one of the select magnets, and the appropriate bridge magnet. The auxiliary magnet essentially has the effect of connecting the inlet circuit either to the bridge commons corresponding to the even numbered outlet circuits, or to the bridge commons corresponding to the odd numbered outlet circuits. (The three right-hand bridge commons correspond to even numbered outlet circuits and to auxiliary magnet 2. The three left-hand bridge commons correspond to the odd numbered outlet circuits and auxiliary magnet 1). The overall assembly of 10 bridge armatures and 6 select bars is thus increased to a capacity of 10 inlets and 20 outlets. With even more sophisticated wiring and the use of 9 bridge commons, up to 28 outlet circuits can be made available to the 10 inlets.

The individual assemblies of crossbar switches are usually arranged in a fan-in–fan-out manner as described earlier in the chapter. In order to pick an appropriate path between inlet and final outlet circuit, the exchange must first examine the dialled digit train. This is done by the register, the action of which is described more fully in the next chapter. Having chosen the outlet circuit required, a path is usually selected by one of two methods. The easiest to explain is the method used in stored program control (SPC) crossbar exchanges. In SPC exchanges (i.e. the most recent ones), the exact path is determined by a special control computer from its knowledge of the instantaneous state of the exchange. The necessary cascade of crosspoints across the exchange is then activated. As an alternative we have the original method of marker control, which was electro-mechanical. In marker control, the final destination outlet is marked, and a large number of trial paths are then set up in a backwards direction across the switch in a cascade fashion. However, only the path which happens to find its way right across the chain of individual switches to reach the desired inlet is actually connected, while all the other trial paths are released.

### 6.8 REED RELAY SWITCHING

In reed relay switched exchanges the individual crosspoints consist of two nickel-iron reeds sealed in a glass tube, approximately 3 cm long, containing dry nitrogen. The free ends of the reeds are plated with gold to give a low resistance contact area. When the contact is not made, the reeds rest in their idle position with their contacts apart. Figure 6.25 shows this assembly.

The whole glass tube is located along the axis of an electromagnetic coil, and when the current is switched on in this coil it induces a magnetic field in the tube. The two reeds take on opposite polarity in the overlapping free ends, so that they are attracted together and a connection is made. When the current in the coil is switched off, the reeds return to their idle rest position, and the contact is again broken. This action can be used as the basis for activating the crosspoints of a switch matrix, as discussed in the early part of the chapter and re-illustrated in Figure 6.27.

Multiple wire connections are achieved by packing the electromagnetic coil or bobbin (as it is called), with more than one reed. Figure 6.28 illustrates a bobbin containing four reeds and which is hence capable of simultaneous four-wire connection.

Reed relay exchanges invariably have stored program control. The exchange processor analyses the dialled number and activates the appropriate switchpoints of the switch matrix by applying current to the coil bobbins.
6.9 DIGITAL SWITCHING

Digital switching differs considerably from the other three types of switching previously discussed in this chapter. All of the three types discussed earlier are what is called space switching techniques. A space switch connects and disconnects physical contacts using a
matrix of switchpoints. When a connection has been established through a space switch, a permanent electrical path exists throughout the duration of the call. This is not so with a digital switch.

Most digital switches use instead a time-space-time (TST) switch architecture; they are not simple space switches. The need for time switching as well as space switching arises from the fact that the line systems connected at the periphery of the switch are not individual circuits; they are usually either 2 Mbit/s (32 channels) or 1.5 Mbit/s (24 channel) digital line systems.

As we saw in Chapter 5, a digital line system carries either 24 or 32 channels in a multiplexed form, which means that the total bit-stream carried on the system has been created by interleaving 8-bit samples of each of the constituent channels. Thus the incoming bit stream to a digital exchange appears as shown in Figure 6.29. The first eight bits are channel 0, or timeslot 0; the next eight bits are channel 1, or timeslot 1; right up to channel 23 or channel 31 as appropriate. Figure 6.29(a) shows the 2 Mbit/s line system frame structure, and Figure 6.29(b) shows the frame structure of 1.5 Mbit/s line systems.
It is no good merely to space switch the digital line systems, as this would have the effect of switching all the individual 24 or 32 channels through onto the same outgoing line system. We need instead to be able to connect any channel (or timeslot) of one incoming digital line system onto any channel (or timeslot) of any of the other digital line systems which are connected to the same exchange. To do this we need both a time-switch capability to shift channels between timeslots, and a space-switching capability to enable different physical outgoing line systems to be selected.

Figure 6.30 shows a digital switch using a time-space-time architecture to switch the timeslots of three 2 Mbit/s digital line systems. On the left of the diagram the incoming or receive timeslots are shown. On the right-hand side, the corresponding outgoing or transmit timeslots of the same 2 Mbit/s line systems are shown. (Recall that any four-wire transmission system, including all digital line systems, comprises the equivalent of two pairs of wires, one pair each for the receive and the transmit directions of transmission).

The incoming (receive) line pairs are fed directly into a timeswitch, the output of which feeds the space switch (shown in the middle). The output of the space switch feeds another timeswitch to which the outgoing (transmit) line pairs are connected.

Imagine now that we wish to switch timeslot 2 in line system A to timeslot 31 in line system B. The space switch allows us to connect line system A to line system B. Point (2) of the space switch allows the receive pair from line system A to be connected to the transmit pair of line system B, while point (6) caters for the other direction of transmission (receive from line system B, and transmit on line system A). However, this by
Figure 6.30 A simple time-space-time digital switch
itself is not enough because it would mean that timeslot 2 in line system A ended up in
timeslot 2 of line system B, and not in the desired timeslot 31 of line system B. The two
time switches allow this conveyance of bits between timeslots. A timeswitch works by
storing the received pattern of 8-bits from an incoming timeslot, and by waiting for
anything up to a whole frame (i.e. anything up to 125 microseconds) in order to feed the
pattern out into any desired outgoing timeslot. For example, delaying an 8-bit pattern by
125/32 microseconds will move the bit pattern from one timeslot of a 2 Mbit/s system to
the next, for example from timeslot 2 into timeslot 3. Similarly, a delay of 2 \times 125/32
microseconds will move timeslot 2 to timeslot 4 and so on. Finally, a delay of 31 \times 125/32
microseconds will move timeslot 2 into timeslot 1 of the next frame (Figure 29).

Why do we need 2 stages of timeswitching in Figure 6.30? For an answer, let us
suppose we want not only to switch timeslot 2 of line system A into timeslot 31 of line
system B, but also to switch timeslot 3 of line system A into timeslot 31 of line system C.
Then, if we only had one time switch (say the one connected to the incoming line pairs),
we would end up trying to superimpose both timeslot 2 and timeslot 3 on the receive side
of the timeswitch onto timeslot 31 before switching the space switch across to its output
side. To get around this problem, the space switch uses its own internal timeslots.

When asked for a connection between incoming and outgoing time slots, the switch
control system carries out a search for free internal time slots on both the receive and
transmit sides of the space switch matrix, and when an idle time slot (number 7 in the
case illustrated) has been found, switching can begin. The incoming timeslot, number 2
of line system A, is timeswitched into internal timeslot 7. Thereafter whenever internal
timeslot 7 comes up, contact (2) of the space switch is activated momentarily and
switches the timeslot content towards the transmit pair of line system B. Finally the con-
tents of internal timeslot 7 are time-switched again, this time into timeslot 31 on the
transmit pair of line system B. Meanwhile the configuration of the space switch is being
changed by the switch control system every 125 microseconds. Necessarily so, as not all
incoming timeslots of line system A are to be connected to the same outgoing line
system (B in this case). The space switch must be ready to send each incoming timeslot
of a single line system into various timeslots of up to 32 outgoing line systems.

At the same time, internal timeslot 23 (the antiphase timeslot of timeslot 7, i.e. the
timeslot + 16 timeslots) is being used in conjunction with space switch contact (6) to
convey the incoming bit pattern on timeslot 31 of line system B to timeslot 2 on the
transmit pair of line system A.

The antiphase timeslot is the timeslot half of the frame after the first allocated internal
timeslot. By always using the antiphase timeslot, we guarantee that the return path will
never suffer internal timeslot congestion, and furthermore we save the switch control
system the effort of searching for a second free internal timeslot. The same method of time-
space-time switching can be used in conjunction with both 1.5 Mbit/s and 2 Mbit/s line
systems. In practice the time-switches are rarely designed to operate at such low rates, but
instead work simultaneously on a number of such line systems which have been previously
multiplexed together. Thus rather than running at 1.5 Mbit/s or 2 Mbit/s (24 or 32 channel
rates), timeswitches are often designed to run at 512 channel or an even higher rate.

It is worth observing that the whole switch operation can in fact be carried out with
only a time switch, and no space switch at all. This is done by multiplexing all the
incoming line systems together into a very high bit stream of interleaved 8-bit channel
patterns; input to the switch is then from one source only and there is no need for a
space switch. For small exchanges this single timeswitch configuration (without space switch) is practicable, and indeed some digital PBXs do function on a time-switch alone. Large public exchanges must be designed as time-space-time (TST) switches, as the high bit rates required to multiplex all the incoming channels together are unattainable with today’s electronic technology.

6.10 PACKET AND CELL SWITCHES

Packet and cell switching, as we discovered in Chapter 1, differs slightly from circuit switching. Although all three types of switching are connection-oriented, only in circuit-switching is the path permanently switched between the two endpoints for the entire duration of the connection. During connection set-up of a packet-switched or cell-switched connection, a path is chosen for the connection via all the relevant intermediate switches and a number of identifiers are allocated (e.g. logical channel numbers) by which the individual packets or cells pertaining to a certain connection may be identified during the course of the call. Each packet or cell of user data is sent with a header containing this identifier.

The switching process stacks incoming packets or cells into buffers, from which they are read out one at a time, in turn. The switch examines the header of each packet or cell and places the whole packet or cell into the appropriate output buffer (according to the logical channel number or connection identifier). When the packet reaches the front of the output buffer, it is despatched to line, so making its way link by link to the final destination. The process is somewhat akin to a postal sorting process, where at each point the postal bags are reopened, and more finely sorted. When the connection is cleared, the identifier (logical channel number or connection identifier) are made free for potential use by other new connections. Critical to the good performance of packet- or cell-switching is the ability for quick processing of packet or cell headers.

Figure 6.31 shows the internal structure of a typical data switching device (for packet, frame or cell-switching. It consists of a bus, or multiple busses, connecting together each of the incoming and outgoing ports. Packets received from any of the line inputs are first stored in input buffers. While in the buffer, the switch analyses the address in the packet, frame or cell header (i.e. the LCN, DLCI or VPI/VCI; we learn about these in Chapters 9, 18, 20 and 26), and based on this information decides for which outgoing port or trunk the packet is intended. A hardware port identification known only internally within the switch is usually appended to the front of the packet, and the timeslot on one of the internal busses is allocated to carry the packet to the intended outgoing port.

Each outgoing port permanently monitors the bus for packets bearing its hardware port identification, and relevant packets are removed from the bus and stored temporarily in an output buffer until they are next in turn for outgoing transmission to line. Thus in Figure 6.31 an incoming packet on the first line and intended for the fourth line would be read to the incoming buffer A, where it would be tagged with the hardware identification of D'. Once the allocated slot on the bus is allocated, the packet would be transferred to the outgoing buffer D', where it might need to wait briefly for its turn to be transmitted to line.
The use of multiple busses running between the buffers of the various ports increases the paths available, so minimizing the delay caused by the 'switching' process. In many cases one of the busses acts as a control bus. Over the control bus information is passed to the various port hardware and associated buffers to regulate their use of the other (traffic-carrying) busses.