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Long Term Developments in Switching [and Discussion]

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Long term developments in switching

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Developments are considered under the headings (i) connection techniques, (ii) control techniques, (iii) interaction of switching and transmission techniques, (iv) facilities offered, and (v) connecting network topology. In each topic, there are open questions. The major forecasts are: (i) the extensive use of electronic digital multiplex connecting networks, compatible with digital transmission systems; (ii) the introduction of optical connecting techniques, which offer both compatibility with optical transmission and some interesting new possibilities for the size and configuration of switches; (iii) the extensive use of stored program control; (iv) the supplementation of central processors by distributed control techniques for the common operational procedures, probably using microprocessors; and (v) the widespread use of semiconductor integrated circuits both for connection and control functions.

1. Introduction

The dividing line between the medium and the long term is rather nebulous; many of the matters discussed here would be equally appropriate to the companion paper by Dr Leakey, and vice versa. The emphasis in this paper is, deliberately, on the more speculative and less established topic of telecommunications switching by optical means. It must be said, however, that on a balanced judgement of the long term prospects, the semiconductor techniques discussed by Mr Roberts and the exchange architecture described by Dr Leakey will remain of major importance throughout the foreseeable future. They will be supplemented rather than superseded.

The main divisions of the subject are: (*a*) connection techniques; (*b*) control techniques; (*c*) interaction of switching and transmission; (*d*) interaction of technology and facilities; and (*e*) connection network topology; and a section is devoted to each.

2. Connection techniques

2.1. *Semiconductor electronic switches*

A large connection network comprises numerous interconnected arrays of switches, through which any desired path may be traced. To the network designer, the basic component is an array capable of connecting any of m inlets to any of n outlets. This may be constructed as an array of $m \times n$ individual crosspoints, i.e. on/off switch contacts such as reed relays, or as a so-called 'multiple' of m switches each capable of selecting one of n outlets by means of a rotational or scanning movement. The early electromechanical exchanges used scanning switches such as uniselectors, two-motion selectors or rotary switches. In recent electromechanical systems, the emphasis has been on coordinate arrays of crosspoints, as in crossbar or reed switches. Digital electronic exchanges have also used the coordinate array, with logic gates as crosspoints. We shall see, however, that optical techniques lend themselves

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equally well to the crosspoint or the scanning approach: the latter may turn out to have its advantages.

Electronic crosspoints could in principle be used for single channels, but their capability of operating in time-division multiplex has long been recognized as their most significant feature (Vaughan 1959). First, it allows the sharing of cost over many channels, as has long been common in transmission: one array of logic gates realizes in effect as many switches as there are channels, a number between 24 and 256 in practice. Secondly, digital multiplex switches can be compatible with digital multiplex transmission systems, as discussed further in §4. There may be a place for analogue electronic switches in small systems, but the dominant electronic switching technique in the major switched networks will certainly be both digital and time-division multiplex for a long time to come. No other approach offers the combination of economy, transmission quality, and proven feasibility.

The digital crosspoint array, known as a space switch (S), must be complemented by a digital time switch (T) in the form of a store, which permits the changing of information from one time slot to another in the multiplex frame. A complete connecting network has the conformation S–T–S, or T–S–T. Both stores and gate arrays, together with their addressing logic, can be realized as semi-conductor integrated circuits. The digital connecting network can, with reasonable economy, incorporate a few stages (3 or 4) using relatively large switches, whereas electromechanical systems, in which the cost of crosspoints is dominant, normally use relatively small switch arrays assembled in a larger number of stages (6–8). The digital configuration permits somewhat simpler control, and much lower blocking probability for a given cost. It is likely that digital groups and trunk switches will have negligible blocking: most of the blocking in the entire network being allotted to the concentrating switches (not necessarily electronic) through which the subscriber lines are connected.

2.2. *Transmission problems of the connection network*

Time-division digital switches use signalling rates of 2 Mbit/s and upwards in practice, and transitions are normally accomplished within a small fraction of the bit period. Thus signal energy components may be present at 10MHz or more. At such frequencies, exchange cabling runs may amount to a substantial fraction of a wavelength: problems of loss, delay, dispersion, and mutual couplings need attention. The traditional line transmission techniques of screening, balancing, termination and regeneration are available, and are adequate for exchanges using 2 Mbit/s highways. For higher speeds, the stripline technique developed for microwave circuits can be incorporated in small switching arrays; good matched and shielded lines are necessary for long interconnections between arrays and units.

Almost all sources of electrical crosstalk become more troublesome as frequency rises. Crosstalk couplings between conductor pairs are due to capacitive or inductive unbalance: switches which are nominally non-conducting exhibit leakage through their internal capacitance. The net effect of crosstalk rises with both signal frequency and the number of sources. Thus problems may be encountered (not necessarily in the same form) with, say, 100 highways each of 60 Mbit/s, or 1000 highways each of 6 Mbit/s. Either of these combinations hasa capacity of about 100000 speech channels, or about 1000 video-telephone channels. It is likely that a large video-telephone exchange (supposing such a thing to be needed) would present severe transmission problems.

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2.3. *Optical switching*

The distinction between electrical and optical carriers of information is, in principle, a rather arbitrary one: both are electromagnetic waves. In switching technology, of course, the distinction is very clear because we need consider only the two extremes. At one end of the spectrum, frequencies up to about 10^8 Hz are conveyed as electric currents, or more precisely transverse electromagnetic waves, through conductors whose transverse dimension is a minute fraction of a wavelength. At the other end, frequencies of about 10^{14} Hz are conveyed in various wave modes (none purely transverse) through structures or regions whose transverse dimensions are at least several wavelengths, and possibly several thousand. The intermediate region, from microwaves to infrared, while significant for transmission has not been explored for switching purposes.

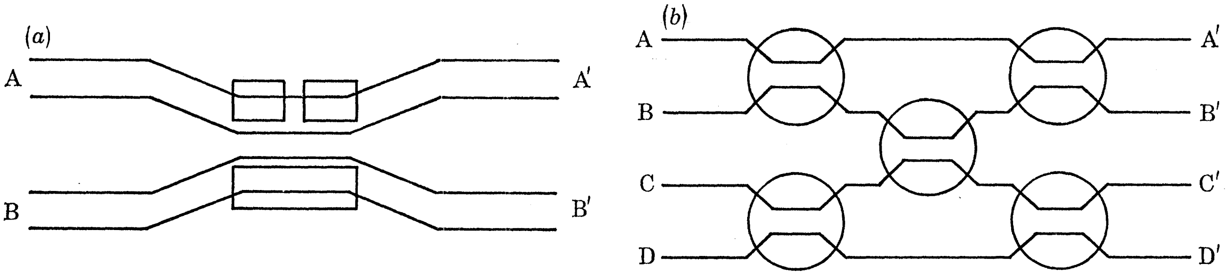

FIGURE 1. Optical couplers as switches: (*a*) the basic coupler as a two-way switch; (*b*) a planar array of couplers.

The reasons for interest in optical techniques of switching are numerous:

(*a*) it offers a possible compatibility with optical transmission, which itself is now in an advanced stage of development;

(*b*) its loss, crosstalk and other properties are virtually independent of the signal bandwidth, so that wideband signals can be switched;

(*c*) it uses, in effect, an extra spatial dimension as compared with electrical switches, which facilitates such interesting configurations as a large $m \times n$ switch without a multiple;

(*d*) basic switches of the crosspoint, changeover, or scanning type are all feasible using various optical effects.

There are many modes of interaction of light with electric fields, magnetic fields, or acoustic waves. Enough investigation has been carried out to identify several effects of particular interest. We may distinguish

(*a*) devices acting as a crosspoint or changeover switch in respect of optical signals in dielectric waveguide, and

(*b*) devices acting as a scanning switch by deflexion of an optical beam in free space.

2.4 *Optical crosspoints in dielectric waveguide*

As an example of the former, we consider electrically controlled coupling between a pair of dielectric waveguides. Waveguides for optical frequencies can be formed by diffusion into various electro-optically sensitive substrates, for example lithium niobate, and waveguide couplers can be made by running parallel guides in close proximity over a suitable length. The refractive index of the material can be varied by applying a potential difference between electrodes plated over the surface; the effective coupling length is thereby changed so as to

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divert most of the energy to the cross coupled path, or to isolate it (Taylor 1973). Devices of this kind can be fabricated as planar arrays interconnecting a set of n inlets and a set of n outlets, as in figure 1 (Taylor 1974).

The practical restriction to a planar configuration limits the size of a switching array. For n inlets and outlets, the number of devices required is $\frac{1}{2}n(n-1)$, and moreover the signal may pass through n couplers each with some loss. If crossover wiring were possible, as with electrical switches, the number of devices would be reduced to a little less than $n \operatorname{lb} n$, with only $\operatorname{lb} n$ devices in tandem.

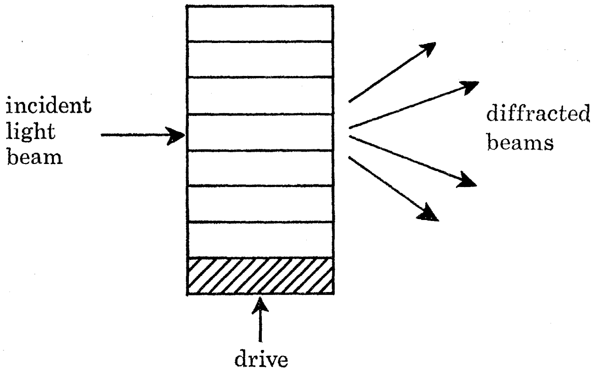

Figure 2. Optical beam deflexion by diffraxion from an acoustic wave.

2.5 *The acousto-optic scanning switch*

As an example of an optical scanning switch, we consider the deflexion of a beam of light by diffraction from an ultrasonic wave. The effect has been known for a long time (Debye & Sears 1932) and has been incorporated in many experimental devices (Gordon 1966) some of which are commercially manufactured on a small scale. The general principle is shown in figure 2. A beam of light is directed onto a transparent crystal, in which ultrasonic waves are excited by means of a piezoelectric transducer. The plane compression wave creates alternate strata of high and low refractive index, equivalent to a moving phase grating, from which light is diffracted. The drive amplitude and the angle of incidence can be chosen to enhance a selected order of diffraction, if desired. A change of drive frequency alters the pitch of the grating, and hence the deflexion angle of the beam.

A possible form of switching array is shown in figure 3 (Cattermole 1972). A rectangular box has at one end an array of inlet ports or light emitters, with a deflector for each inlet. At the other end is an array of detectors or outlet ports. By setting the appropriate deflexion angles, a signal modulated on to a beam of light can be directed on to a selected outlet. Distinctive features of such a switch are:

(*a*) by deflexion along two axes, a 2-dimensional array of outlets can be scanned; and

(*b*) the same outlets are accessible to all inlets; there is no need to construct a 'multiple' of similar devices wired in parallel.

An important property of a deflector is the ratio between the total range of angular deflexion and the angular resolution of the output beam. This sets an upper bound to the number of resolvable spots, and hence the size of the switch. This upper bound may be rather large. Work with experimental devices suggests that the number of resolvable spots in one dimension can be as much as 100, hence a two dimensional array could have 10000 outlets, a much bigger switch than is attainable in a single stage by any other technique.

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There would be, of course, problems of precision, and also (since the angular deflexions are small) of optical magnification or folding of the paths. More fundamentally, there is a joint bound on resolution and switching speed. Resolution improves as the aperture of the device (measured in optical wavelengths) increases. But a change in deflexion angle is accomplished by replacing one virtual grating by another; this change occupies (at least) a time interval equal to the aperture width divided by the velocity of the ultrasonic wave. Experiments with lead molybdate devices at an optical wavelength of 633 nm (Rabson 1974) yield a joint bound

$$\frac{\text{change-over time}}{\text{number of resolvable spots in one dimension}} \geqslant 16\times 10^{-9}\ \text{s}.$$

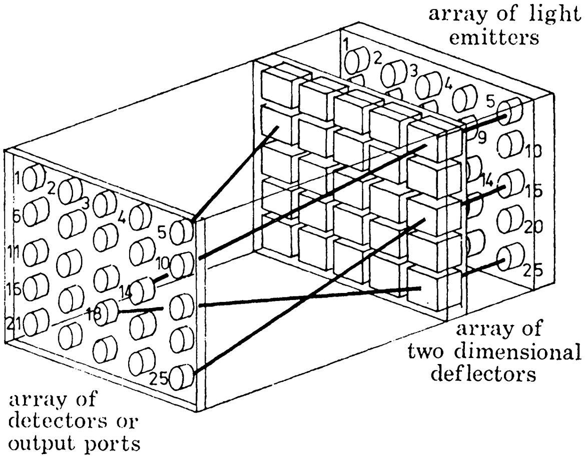

FIGURE 3. A large optical switch using deflectors.

The change-over time would be negligibly small for single-channel communications, but something of an impediment to time-division multiplex (t.d.m.) operation. However, a t.d.m. optical switch can be envisaged (Cattermole 1972; Rabson 1974) which separates odd and even channels by means of a fast two-way switch employing electro-optic diffraction (St Ledger & Ash 1968): this provides an adequate guard time for the slower acousto-optic switch to change over.

Crosstalk can occur in such a switch through imperfect resolution, imperfect mechanical registration, optical scattering, and mutual couplings between electronic drive circuits. All these, however, are virtually independent of the signal bandwidth, and so a large switch for wideband signals appears to be feasible.

3. CONTROL TECHNIQUES

3.1. *Central processors and their limitations*

As we have seen from the companion paper by Dr Leakey, telephone switching systems have exhibited a trend towards greater centralization of control and control signalling. The first system to incorporate stored program control (s.p.c.) (Bell Telephone Laboratories 1964) carried centralization about as far as it could go within the confines of one large exchange. The major properties of such a system include:

(*a*) all or most control operations are dependent upon a central processor;

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(*b*) large storage capacity is required both for an elaborate set of programs covering all operating, maintenance and management procedures and for the data associated with subscribers, routes, and so on;

(*c*) with all the eggs in one basket, every conceivable precaution must be taken against failure, hence the replication of processors and stores, and arrangements for reconfiguration and recovery in the event of breakdown;

(*d*) the versatility in respect of facilities, numbering, routing, signalling, and so on which is generally claimed as an advantage of s.p.c. is indeed attainable, but at a substantial cost both in initial provision and in development and maintenance of software.

One obvious effect of these properties is to make such system quite uneconomic for small exchanges. They have been effective, and economical, when developed by large authorities with massive resources for use in their larger switching centres. But if stored program control is to become more widely or even universally employed in telephony, then there must be some reduction in

(*a*) the overhead cost of hardware and software attached to any one exchange (so as to make small exchanges economic), and

(*b*) the overhead cost, especially of software development and maintenance, attached to the generic type of exchange (so as to facilitate small scale use or gradual introduction).

It might, of course, be contended that the dominant problems of telephony are in the large traffic centres, so that economy of scale is a benefit rather than a problem. However, this is not the whole truth. Public telecommunication services must, in general, take the distribution of population and economic activity as given, and provide service wherever it is required. Human settlements are of diverse size, from village through town and city to metropolitan conurbation. A wide range is predicted by the central-place theory of economic geography, and is an empirical fact of long standing (Lloyd & Dicken 1972). From the simple reciprocal rank/size distribution of settlements, which is of widespread occurrence (Lloyd & Dicken 1972, p. 36) it is easy to deduce that in a large territory some seven-eighths of all settlements have less than the average population, and contain about a quarter of the total population. Moreover, it is now widely recognized that excessive build-up of the metropolis at the expense of rural areas is socially and ecologically unstable. We may therefore suppose that the diversity of settlement size and type will persist, and that telecommunications networks will include exchanges of all sizes from (say) 100 lines to 100000. This is equally true in the developing countries (where much of the population and the economic potential is in sparsely populated areas) and in the industrialized countries (where a basic telephone network has penetrated almost everywhere, and much of the business lies in extending it by modest instalments).

Approaches to the problem of incorporating modern control techniques in the smaller centres have followed two apparently contradictory principles, of greater and lesser centralization respectively.

3.2. *Central control of a multi-exchange area*

Small terminal exchanges are necessarily connected to at least one (and usually only one) nodal point in the network, namely a tandem or trunk exchange. It is possible to utilize a common control system for a star network comprising the nodal exchange, and a group of satellite or dependent exchanges each connected to the node by a group of switched circuits for speech traffic and a dedicated circuit for control signalling. The satellites could, in the extreme, be small unattended centres having only the minimal equipment for subscriber

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line connection and concentration. The nodal centres would have a full range of operational, maintenance, management and accounting facilities, including of course the central processors and memories. A sufficiently large multi-exchange area could support the capital and running costs of a central control complex, provided that the latter were used efficiently in their new mode of working.

Clearly there will be a loss of efficiency due to remote control: some extra run time will be taken up with data assembly, acknowledgement procedures, error checking, etc., for operation over the unique signalling channel. There are also extra costs and hazards. None of these factors is prohibitive. Area control schemes have been considered by several authorities: the most complete development, the French 'Platon' system (Pouliquen & Tallegas 1972) has been carefully evaluated during practical trials, and there is no reason to doubt that it is feasible. However, many people have doubted whether it is the best solution, all things considered.

3.3. *Distributed control*

The second way of avoiding the problems of centralization is to divide the control functions between many units, each of which perform a subset of the functions for a subset of the lines or calls. Typical units might be, for example: (i) a line-scan unit which scans a block of 1024 subscriber lines for calling conditions; (ii) a small group of register/senders; (iii) a marker identifying terminal-pairs to be connected via a 3-stage switch; (iv) a supervisory unit for a small group of trunks. The number of units of any type will depend on the traffic to be carried and the lines to be served, though not necessarily in strict proportion. Failure of any one unit may reduce traffic capacity, but will not put the whole exchange out of action.

To the telephone engineer, unlike the computer designer, all this is completely conventional. It has been incorporated in all the more modern electromechanical exchanges and in many semi-electronic exchanges. It is the principle which has for many decades permitted telephone exchanges to operate with high system reliability while using imperfect and unreliable components. But, like many eternal truths, it seems to need restatement from time to time.

The problem is then to obtain some benefit from modern technology, including computers and software, within the framework of a fairly traditional system architecture, or of a new one based on the old principles of traffic and function division (Hills 1974). There are two reasons for supposing this to be possible.

First, the development of economic small processors in integrated-circuit form, and of small random-access and read-only memories, permits the use of s.p.c. techniques on a small scale. This is discussed further in §3.4 below.

Secondly, the techniques of structured programming devised for s.p.c. systems (Hills & Kano 1976) give a rational basis for functional design and partitioning of any switching system; individual functions can be realized by special-purpose hardware, or micro-processors, or as procedures within the repertoire of a central processor, according to the current economic and technical constraints and without major changes in system architecture.

3.4. *Microprocessors*

There seems to be no definition of a microprocessor other than a digital processor constructed on one or a few integrated-circuit chips. This leaves open the question of what it can do. We will examine the possible limitations to the performance of a microprocessor (as compared

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with a relatively large computer) under three headings: (i) the repertoire of procedures it can perform; (ii) its speed; (iii) the associated storage capacity.

The instruction set of a typical microprocessor is smaller than that of a typical large computer, but this does not in principle impose any limit on the repertoire of procedures which can be executed. Any computable function can be computed using a minimal instruction set smaller than those normally available. Practical limitations are therefore those of speed and storage.

The speed of a microprocessor is reduced by two factors. First, given that the word length and instruction set are restricted, it may take more machine cycles than a bigger computer, for a given procedure. Secondly, with current m.o.s. technology, the machine cycles are slower than with the best available semiconductor logic. The rate of executing telephonic operations is therefore restricted, and we need to know whether it is fast enough to be useful. The best evidence is empirical: small exchanges have been constructed using currently available microprocessors to execute some or all of the telephonic control functions. At least one model of private automatic branch exchange is now commercially available in which a microprocessor scans 120 lines and 28 trunks every 10 ms, on interrupt, and sets up connections via a semiconductor switch. Clearly, such processors can operate at suitable speeds for incorporation in traffic- and function-divided control units such as those discussed in §3.3, and are capable of more versatile use so long as their traffic capacity is not exceeded.

The final criterion is storage capacity. It is reasonable to associate with a microprocessor a small store of comparable cost and size. This implies limitation to a few thousand words: maybe 1 k of r.a.m. (random-access memory) and 2 k of r.o.m. (read-only memory) at current prices, potentially perhaps 4 times as much in the medium-term future. This is adequate for programs for a small set of telephonic procedures, for call data and routing data in a small exchange, but falls far short of the full storage requirements for an s.p.c. system, which can run to several hundred thousand words of program alone. Storage costs are still falling, but there is no prospect of memory on this scale becoming trivially cheap. Here, therefore, we encounter a significant limit.

3.5. *Hybrid control*

We have distinguished centralized and distributed control as alternatives, but we now consider the possibility that they are complementary, namely that each should be used for an appropriate set of functions.

The very large set of programs provided for a system such as ESS1 or D10 can be classified (admittedly with some fuzzy edges) as follows:

(*a*) common operational procedures such as line scan, call set-up, and trunk supervision, requiring simple repetitive operations in very large numbers;

(*b*) less common operational procedures such as special telephonic services, requiring somewhat more complex operations with fewer repetitions;

(*c*) operational procedures available as part of a generic program, but not invoked at a specific centre;

(*d*) maintenance, management and statistical procedures in regular use but not necessarily available on demand at all times;

(*e*) procedures required only for development or extension of the system.

In general, the common operational procedures occupy a small fraction of the total program store. For example, the Japanese D10 system includes some 2000 procedures, but over 90%

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of the run time is accounted for by only 20 procedures. It is clear that the common operational procedures can reasonably be implemented in a different way from the others. The response of the D10 designers is to store program for the common procedures in executable code, but to use an interpretive mode for many of the less common operational procedures. This is an appropriate distinction for a big system: other distinctions more relevant to the problem identified here may be drawn as follows:

1. Common procedures may be implemented at all switching centres including small satellites, others only at a nodal exchange, as discussed in §3.2. The 'Platon' system goes some way in this direction.

2. Common procedures may be implemented in small units, using either special-purpose hardware or microprocessors with the appropriate subset of programs: other procedures may be executed by a central processor. Such an exchange could have a limited but useful operational capability even if the central processor suffered complete breakdown (Hills 1972).

The conclusion for future development is that fully centralized control, with its attendant problems of economy and reliability, may be supplemented by a distributed mode, akin in its general architecture to the earlier systems, but drawing on recent developments both in microcircuit technology and in software structures.

4. Switching and transmission

Until recently, the techniques of switching and of multiplex transmission have been entirely unrelated, and the only feasible interconnection has been of voice-frequency channels. This has imposed both the monetary cost and the transmission impairments due to modulation, demodulation and signal conversion at the interface. It has been recognized from the early days of pulse code modulation that a digital integrated network would avoid these penalties (Vaughan 1959). The digital multiplex signals in p.c.m. transmission and switching systems can be compatible, so that interface costs are minimal and transmission impairments nonexistent.

The economic argument for the digital integrated network is now classical (Cattermole 1969). Consider a star network, with a nodal switching centre and several junction routes. On junctions of suitable length, digital transmission systems are economical even with analogue switching; indeed they are now extensively used. Similarly, though with less certainty, digital switching systems may be economical in isolation if the traffic carried is large enough to benefit from their economy of scale. The presence of either makes the other more beneficial, due to the saving of interface costs, so that the fully digital star network may be the most economical solution even at distances below the critical value for transmission systems, and traffic below the critical value for switching systems. Figure 4 shows graphically the régimes in which each combination of analogue and digital techniques is most economical: the general form of the four regions persists over wide ranges of cost parameters.

Arguments of this nature may be developed in detail for specific networks. The Trunk Task Force of the British Post Office has concluded that, in the long run, a fully digital solution is the most economical for the U.K. trunk network, and also has substantial transmission advantages (Breary 1974).

In the long run, similar arguments may well apply to optical techniques. Transmission over optical fibres is now at an advanced stage of development and should see substantial application

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over the next 10–15 years. It appears to be suitable for all parts of the switched network: for trunk and junction routes initially, and for local distribution also in the event that wideband facilities of almost any type are to be used extensively. Present practice is to revert to electrical signals for regeneration, multiplexing or switching. It is to be expected that all these functions will eventually be performed directly on the optical signals: and, as described in §§2.3–2.5, the techniques for switching can be discerned in outline even now, though a good deal of development remains to be done.

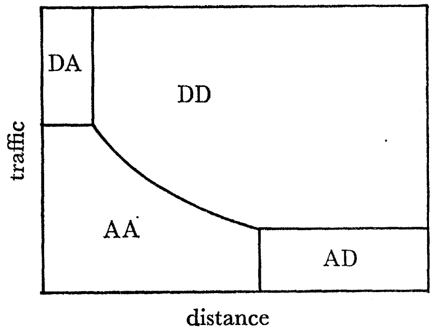

FIGURE 4. Economics of digital techniques in a star network: AA, analogue switching and transmission; DD, digital switching and transmission; AD, analogue switching, digital transmission; DA, digital switching, analogue transmission.

5. FACILITIES

5.1. *Message facilities*

It is now part of the conventional wisdom that the switched telecommunication network should at some future time provide for modes of communication other than telephony, notably for videotelephony, facsimile and enhanced data facilities of various kinds. We may distinguish:

(*a*) Facilities which could readily share the telephone-network plant, and do not raise any essentially new problems.

(*b*) Wideband facilities such as videotelephone which need new transmission paths and connecting networks but could use the telephonic modes of signalling and control. These present the strongest case for optical techniques of switching and local distribution.

(*c*) Facilities such as interactive modes of data transmission which place no stringent requirement on transmission capacity but require new signalling and control capabilities, primarily to secure rapid response. These present the strongest case for packet (as opposed to circuit) switching.

5.2. *Control facilities*

In the field of telephony, there are many facilities which offer the user some enhanced measure of control. Abbreviated dialling, automatic repeat attempts, camp on busy, automatic transfer, and so on, are well known features of modern private automatic exchanges. It is more difficult to incorporate them in a large multi-exchange network, but there seems no doubt that some national telephone networks will develop them over the next decade or so. The primary requirement, given a suitable switching system, is an adequate means of sending control signals between exchanges. The companion paper by Mr Ketchledge indicates that the c.c.i.s. (common channel interoffice signalling) technique, in conjunction with the current generation of e.s.s. (electronic switching systems) is expected to furnish all the required capabilities in the United States.

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The author's belief is that rather too much of such development has been directed to aiding the calling party, and not enough to protecting the called party from sheer communication overload. The telephone can already be an intrusion and a distraction. It is so primarily because

(*a*) the called party has no possible responses other than to answer the telephone or let it ring: he cannot, for example, bar incoming calls temporarily, bar certain categories of call, or identify the calling party and decide what to do;

(*b*) the calling party has no knowledge of the current status or preference of the called party, except in so far as he answers the telephone or does not: he cannot, for example, discern that the called party is busy and would like to take only urgent calls.

One can envisage a system of selective bars which could be set at various levels; they might be irrevocable, or more usefully they could be overridden by the caller who would make his own judgement in the light of information presented to him (Cattermole 1971). Such bars and overrides would be equally worthless if always used or never used: it is to be hoped that a code of practice, reinforced by social pressures, would cause them to be used in a restrained and reasonable manner. But the material provision, in the form of signalling and control systems, must be there to provide a chance for a more subtle and flexible telephone etiquette to evolve.

6. Connection network topology

The present inter-exchange network is a hierarchical tree, with an overlay of direct circuits. The internal trunking of an exchange is a multistage network in which each rank of switches is traversed in a definite order. Is there an alternative?

There have been a number of attempts to conceive some more homogeneous form of network, lacking the hierarchical definition of nodes and the specified sequence of traversal. The primary aim is to provide numerous alternative routes so as to maintain network reliability despite local failure or congestion.

It is difficult to define routing algorithms, or analyse performance, unless a structural symmetry of some kind is imposed on the network. Probably the most clearly defined structure which has been proposed as an alternative to the conventional form is the Cartesian product network (Cattermole & Sumner 1977), whose topology is based on that of the general multi-dimensional measure polytope. It remains to be seen whether such explorations will lead to any practical outcome.

7. Conclusion

The main developments envisaged are:

(*a*) the extensive use of electronic connecting networks, principally digital time-division multiplex, which in conjunction with digital transmission systems will form a compatible integrated trunk network;

(*b*) the introduction of optical techniques of switching, probably in association with optical transmission over fibres;

(*c*) the extensive use of stored program control implemented by large central processors;

(*d*) the supplementation of centralized control by distributed control, divided by traffic and function, using s.p.c. procedures implemented by microprocessors;

(*e*) semiconductor integrated circuits widely used as a basis for (*a*) and (*d*);

(*f*) wideband message channels, probably using optical techniques;

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(*g*) enhanced control facilities based on the widespread use of modern control and signalling methods.

These are all technical possibilities. Their realization will depend not only on technical progress and economic feasibility, but also on the existence of a general architecture for the switched network which can accommodate evolutionary development. If past experience is any guide, this last requirement is the most difficult to fulfil.

I am indebted to my colleague Dr M. T. Hills for many insights into the problems of telephonic control, some of which are used in §3 of this paper.

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Discussion

M. T. HILLS (*Department of Electrical Engineering Science, University of Essex, Wivenhoe Park, Colchester, Essex*). The history of telecommunications manufacturers to date has shown that they have achieved a natural monopoly of supply because of the need for specialist electromechanical components. However, the various speakers today have mentioned two trends:

(*a*) an increasing reliance by telecommunications manufacturers upon semiconductor devices available on the open market;

(*b*) a move to digital switching systems which require no special components.

This implies that it is now possible for any electronic systems manufacturer to make switching

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systems in the future. This trend is already visible in the p.a.b.x. market in N. America. The questions I should like to ask are:

1. What is to prevent outside suppliers providing 'plug compatible' local switching systems?
2. Does Professor Cattermole see his optical switch as a possible means for the traditional suppliers to maintain their 'natural' monopoly?

K. W. Cattermole. I share the view that the techniques of telecommunications and other electronic/information systems are converging, and that this will probably affect the distribution of business among the manufacturing companies. Even if no 'plug-compatible replacements' emerge, the added value contributed by the established manufacturers will diminish sharply unless they have a stake in the manufacture of electronic components and integrated subsystems.

The optical switch will not change this trend. First, the skills required for manufacture of electro-optical devices are, if not identical with, at least generically similar to those used for semiconductor devices. Secondly, I believe that optical and electro-optical techniques will be widely used for information processing outside as well as inside the telecommunications field. Thirdly, any electro-optical system will need a good deal of associated digital electronic circuitry. Taking these points together, the leading manufacturers of future systems incorporating electro-optics could well be those with a good record of innovation and manufacturing competence in electronics.

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