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Naval communications systems

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NAVAL COMMUNICATIONS SYSTEMS

A Thesis

By

Louis Piollet Spear
Lieutenant Commander, USN

May 1947

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A Thesis

Submitted to the Faculty of the
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Partial Fulfilment of the Requirements
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in Engineering Electronics

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Lieutenant Commander, USN

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Approved: _____
    Dean of the Naval Postgraduate School

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NAVAL COMMUNICATIONS SYSTEMS

ABSTRACT. This paper attempts to determine the require-
ments of communication systems in general, and naval
communications specifically. Unlike commercial commun-
ications, naval system design must solve the problem of
extreme speed without the loss of reliability, and ex-
treme flexibility without overcomplicating operation or
increasing physical bulk. A comparison is drawn between
present naval communication practice and systems which
are practically attainable if the potentialities of the
communication art are fully exploited. Although the
field selected for this paper is so broad that it is
discussed, for the most part, in general terms, some
phases are treated in detail to illustrate the manner
in which seemingly unimportant detail affects overall
system design. The fundamental truths and relationships
are emphasized, for they then serve as a point of de-
parture into the more complicated relations of system
details. Finally, the design requirements of a prac-
tical inter-ship naval communication system are discussed
and a solution offered as an example of system design.
The problem of communication security, and the many
special systems for obtaining security, is purposely
not discussed.

NAVAL COMMUNICATIONS SYSTEMS

I GENERAL

1. Background

Radio was but ten years of age when the United
States became involved in the First World War. In 1907
U.S. Patent 841387 was obtained by Lee deForest and the
vacuum tube, which had been merely a laboratory toy of
some interest, became the powerful tool which in forty
years was to cause a revolution in every field of human
activity. By 1917 the infant radio had cut its teeth
in disaster at sea and the electron art was emerging as
a full fledged science in its own right, with the con-
tinuing development and application of physical theory
to the design of equipment. In that year, trans-oceanic
telephony and radio broadcasting were being played with
on an experimental basis, but for the most part radio-
telegraphy was well intrenched in commercial and mili-
tary practice, and the "brass pounder" ruled the radio
wavelengths.

In the two decades intervening between the First
World War and the outbreak of the Second World War, radio
communications matured and expanded with the full force
of mass research by the commercial communications labor-
atories, employing hundreds and thousands of individual

specialists, each contributing his small share to the
total understanding. As the art expanded, the role of
the individual in this expansion became smaller and
more specialized following the well established pattern
of the growth of scientific knowledge. The early ex-
perimenters were versatile fathers to their growing
child, serving alike as designer, builder, and operator.
It was still possible for one mind to encompass complete-
ly and understand the then limited field of radio and
electronics. With growth, however, the functions of
research, design, and operation became separated among
groups of special interest and the operating functions
became, in general, divided from the design function,
with the operating interests determining the pattern of
development.

The operator is concerned, not with things, but
with methods and the economic implications of those
methods. Under the compulsion of these economic consid-
erations, and under the guidance of the operating groups,
commercial communications have increased in efficiency
by exploiting new technical developments and putting
them to work economically in transporting intelligence
from place to place. The old fashioned telegrapher has
disappeared from commercial communication practice,
being replaced by the automatic telegraphers, -- the

automatic Morse systems, and the teleprinter. The new
art of voice transmission has created systems opera-
tionally simpler than telegraphy, the radio-telephone,
of which radio broadcasting is a branch. The even newer
arts of television and facsimile have yet to prove them-
selves economically in wide scale operation, being in
many respects yet in the experimental and developmental
stage. At every level in the rise of commercial commun-
ications, new proposals have been made and subjected to
the most searching examination from the operating view-
point, for regardless of the ingenuity of the technical
design, the new proposals must compete with other sys-
tems on an economic basis.

2. Present Naval Practice

There is no need to belabor the obvious. It is
widely known that, commercially, radio communications
have had a continuous record of progress and increased
efficiency through the economic exploitation of the ad-
vances of physical research from the days of deForest's
patent. It has been mentioned here only to provide a
self evident contrast with naval communications.

In the Second World War, though technical advance-
ments had been made in materiel far beyond that of World
War I, the technique of handling traffic had not advanced

apace to utilize fully the new capacities developed in commercial practice during the intervening years. The fleet radio circuits were manned in World War I by the old professional telegrapher. World War II recruited the amateurs, the "hams", to man the code circuits. The telegrapher has now disappeared and the amateur is turning to the more exciting realm of phone. There is no longer any group in the United States that remains well versed and interested in telegraphy to serve as a pool of trained communication personnel if we persist in handling fleet traffic by manual code. There are clearly but two alternatives. The Navy can embark upon a program of system modernization designed to simplify operations, or it can prepare to train personnel in outmoded and difficult operational techniques for the next emergency. The former will allow us to train a few groups in simple system practices; the second will require us to train large numbers in complicated procedures and mechanical operations.

Although the shore communication systems have been modernized by the employment of commercial equipment and techniques, the sea going equipment has seen little improvement, systematically, since the first days of radio. The day of mechanization has yet to come, and the great bulk of traffic is still handled by manual labor.

Fleet communications pose a problem peculiar to itself and unlike any met in commercial practice. The problem is not so much one of scale, but of complexity. Commercial communications involve, for the most part, point to point circuitry with subsidiary switching problems to achieve flexibility. Fleet communications circuits are largely multi-point conference circuits, inherently more complicated than point to point. In addition, fleet circuits must be provided by radio, rather than wire, because of the water borne, mobile nature of the stations, and radio in itself imposes restrictions upon systems design not encountered in the equivalent wire circuits.

The speed of a communications system is measured, not alone in words-per-minute of transmission, but also in the elapsed time from originator to addressee. The true test of system speed must include time lost in preparation before transmission and processing after reception. Any time during which the message lies idle in the channel from sender to receiver must be charged as undue delay to be eliminated. The best system will have a uniform rate of traffic flow over its entire length, and traffic will not pile up in the bottle neck of a slow traffic link.

In present practice, the greatest delays do not

occur between the sending key and the receiving head-
phone, for even moderate sending speeds are usually
sufficient to clear waiting traffic on most fleet cir-
cuits. The greatest delays occur before transmission
and after reception. No real attempt has been made to
extend the communication system to include the province
of internal message handling before and after trans-
mission as an element of the technical design problem
for communications equipment. It has not been suffi-
ciently recognized that the communication system is a
man-machine combination, and, in any such system, the
machine must be designed to comply with the limitations
of the human element. In the early days of radio, the
capabilities of the man were superior to the machine he
operated and the human limitations were not evident.
The demands of modern naval communications are greater
than the human operator can handle, and the machine has
been developed technically to the point where it can
handle traffic much faster than the man. It is now time
to design the machine to relieve the load on the human
and thus increase the over all speed of the system.

The operational steps in the communication channel
are set forth in Figure 1. Actual systems may be more
elaborate, but no system can have fewer operations with-
out some sacrifice to performance. The present province

ORIGINATOR

FILING

TRANSCRIBING
   INTERNAL ROUTING

ENCODE
   CHECK DECODE

TRANSMISSION

RECEPTION

DECODE

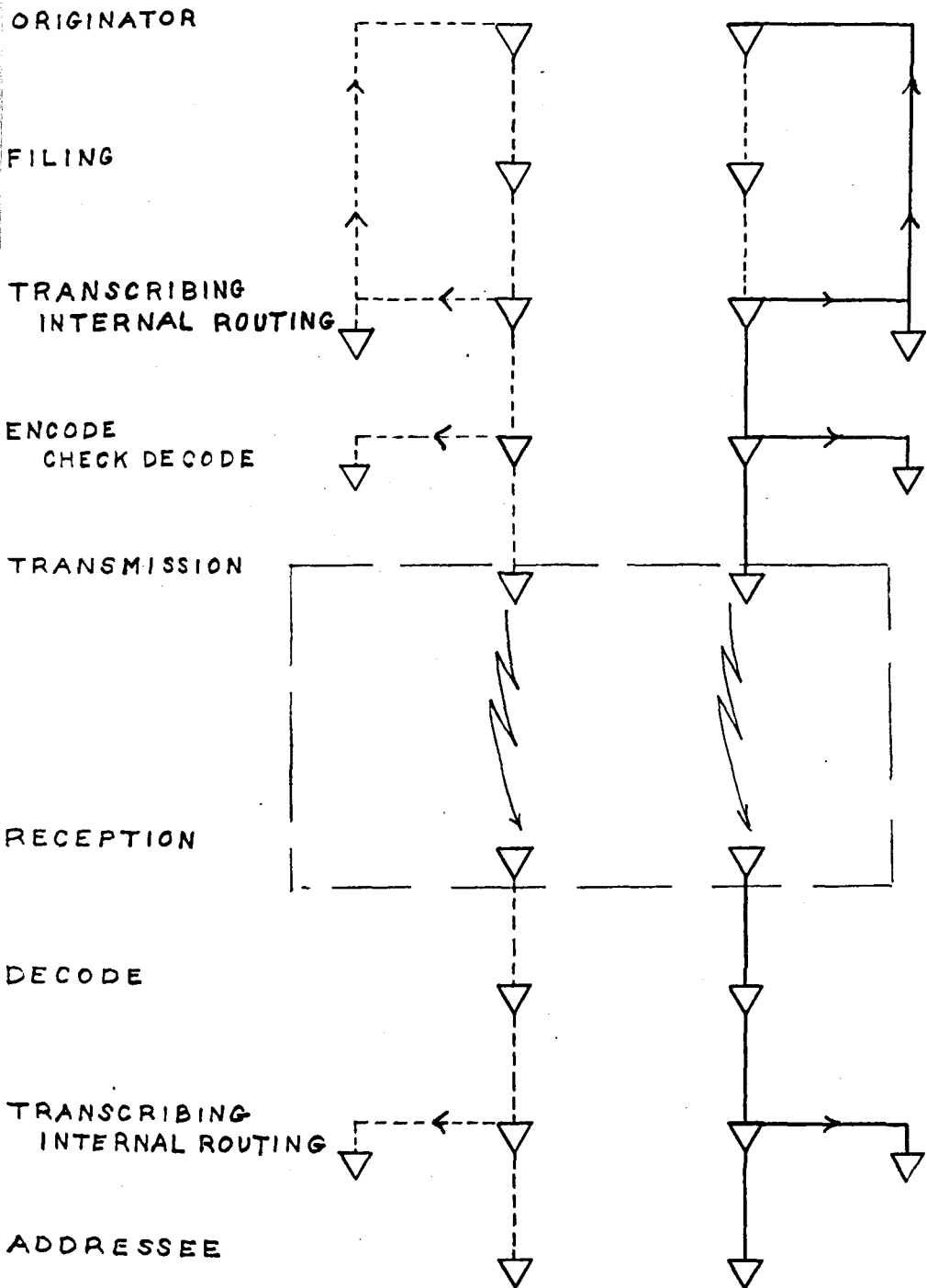TRANSCRIBING
   INTERNAL ROUTING

ADDRESSEE

Fig. 1   Basic Message Handling.

- - - -   Manual Transfer
———   Electrical Transfer
▽   Operation Performed

of system design is that which concerns transmission and
reception, the operations within the dotted rectangle.
The left hand diagram represents the present chain of
message handling. The message leaves the originator and
enters the communication system for filing, transcribing,
and internal distribution. The movement from one opera-
tion to the next is manual. Each operation represents
a fairly specialized function requiring personnel devot-
ing their entire attention to that operation and subject
to the possibility of ever prevalent human error. The
operation of encoding and check decoding entails the
greatest delay and opportunity for error because of its
complexity.

At no point in this chain, after the message leaves
the originator, is there any operation that cannot be
performed automatically by electronic or mechanical
machinery, and performed faster and more accurately. The
installation of such equipment would serve the triple
function of eliminating human error, improving the sys-
tem speed by electrical operation and distribution, and,
incidentally, eliminating thereby the need for a large
staff of highly trained operating personnel. The right
hand line diagram shows that, although none of the basic
steps are eliminated, most of the operations can be mech-
anized and interconnected electrically.

3. Possibilities of Modernization

The teleprinter was developed commercially to re-
place the telegrapher and the manual message handling
problem which he entailed. The input motivation re-
quired for the teleprinter is particularly adapted to
the human operator. There is no unusual problem presen-
ted by the teleprinter that cannot be mastered by the
ordinary stenographer, or yeoman, in a very short time.
In fact, a person completely inexperienced as to typing
technique can still operate the teleprinter faster than
most telegraphers can clear traffic with the Morse key.
The output is in the form of electrical telegraphic im-
pulses which automatically actuate all similar machines
connected on the same wire or radio link. Therein lies
the greatest virtue of the teleprinter; the ability to
make a positive, direct record of the intelligence being
transmitted or received in many different stations at
once, making at the same time a number of copies for in-
ternal distribution. This eliminates the redundant op-
erations of transcribing and manual distribution. In
addition, the teleprinter lends itself admirably to the
mechanical transpositions and substitutions required for
machine coding and decoding which further permits the
elimination of the redundant motions involved in coding
and check decoding. And lastly, the intelligence from

one teleprinter may be recorded for automatic retrans-
mission or relay.

It is readily evident that there is much to be
gained by mechanization of the communication system.   In
every branch of engineering it is well known that the
human element of a machine-man combination is the weak-
est and most susceptible to error when performing rep-
etitious or monotonous operations.   Present naval prac-
tice requires personnel to spend many hours performing
operations of duplication and monotonous repetition.
The reception of the Morse radio signals is a subjective
recording operation and must operate through a human link
with the attendant susceptibility to error from fatigue.
After recording, the message goes through several sub-
sequent stages of transcription in decoding and internal
distribution.   And at no stage are the operations per-
formed in a positive, non-subjective manner which elim-
inates the chance of human error.

The degree of human error present in any operation
is a function of experience, complexity of the operation,
the physical and mental condition of the human link, and
environment.   Experience is not a controllable factor in
wartime, for the press of mobilization will not always
allow adequate training of personnel in the many exacting

duties of communications. Some operations lend them-
selves nicely to human manipulation, while others are
mechanically or psychically difficult for the human
body to perform. These factors are partially control-
lable if the system is designed with consideration for
the adaptability to the human machine (and this provid-
ing that the human machine can be analyzed sufficiently
accurately as to its best modes of operation.) The
physical and mental condition of the human machine is
an almost uncontrollable factor, for it is subject to
many variable influences. Likewise, the environment is
only partially controllable, for it is secondary to many
other considerations, particularly on shipboard.

It is evident, though, that if a mechanical or elec-
trical system can be substituted for the very fallible
human, many of the problems of procurement, training,
and system error which the human element engenders, can
be eliminated. The design and procurement of the neces-
sary complicated equipment, and the training of competent
personnel to service and maintain that equipment, does
pose a separate problem, but a problem that can be solved
in the leisure of peacetime operations, and not under
the press of national mobilization. It is probable that
any future war will develop so rapidly as to preclude
the opportunity to develop a competent communication

personnel, and the training cannot be accomplished successfully in peacetime. It is imperative that a program of survey and modernization be undertaken now, when time is not of the essence, rather than to wait until a time of national crisis when it will become apparent that our present concepts of systems design are too hopelessly inadequate and antiquated to cope with the rapid fire developments of modern warfare.

The electrical system is designed within the framework of natural laws, and these laws are, unlike the laws of human behavior, constant and knowable. Consequently the machine system can be exactly controlled and varied to meet the requirements of the particular service, and made independent of undesirable factors. Such a system will be invariant, not only with widely varying operating conditions, but also with time. Communications represents a basic social relationship which is independent of any special equipment used. The very basic concept of communications is to get intelligence from one person in one place to other persons in other places through channels designed to overcome intervening obstacles. It is immaterial to the intelligence how these channels are established as long as they are capable of handling the intelligence and overcoming the obstacles. If these channels are once established, it

should then be possible to alter the <u>component</u> design
of the system elements, without the necessity of alter-
ing the <u>system</u> design, if the end result of the opera-
tion remains unaltered. Referring again to Figure 1,
it is evident that the component equipment at any single
point of operation may be altered if the function of
the equipment remains unchanged. A basic system can be
built up, designed for the special requirements of the
naval service, which is invariant, but will allow for
expansion and modernization without in any way affect-
ing the basic manner of operation. This is predicated
upon the premise that the basic system is designed ac-
cording to the needs of the service and within the
limitations of the natural laws of engineering. It is
first necessary to determine the requirements of the
service, and then to determine the natural technical
limitations to fulfilling these requirements.

II COMMUNICATIONS SYSTEMS

1. Naval Communications

It has been mentioned that one of the distinguish-
ing features of naval communications is multiplicity.
The originator seldom addresses his communication to
one single activity, nor is the same message of the
same degree of importance to all addressees. That which
is highly important to one party may be of only inform-

ative interest to another. Also messages do not all
have equal importance in their impact on the naval es-
tablishment. It is necessary that the various classes
and levels of traffic be defined and classified accord-
ing to the structure of the navy itself.

The exercise of effective naval command is depen-
dent upon two factors; efficient organization and
efficient communications. The naval commander obviously
cannot hope to accomplish his task unless the forces
under his command are efficiently organized and deployed
towards that end. It is also clearly apparent that he
cannot accomplish his task if he is unable to communi-
cate his will to his command. The first aim of communi-
cations is to serve naval command, and must always be
subordinated to this purpose.

Command is not the only function of the naval
commander. Problems subordinate to his basic command
problem are the complementary freedom of action problems
involving security, logistics, training, intelligence,
and communications itself. All of these problems must
be solved by the commander himself, and they cannot be
implemented unless he can make his decisions known, not
only within his command, but to all the coordinate and
superior organizations with whom he must coordinate his
decisions and actions. Thus logistics require the in-

terchange of information between the commander and the
logistic agencies upon which he is dependent. Intelli-
gence requires channels of communications from the in-
telligence source to the commander. Communications
involves the commander in complementary details of
traffic handling and procedures within the limitations
of the system equipment provided to him. The better
the equipment with which he is to work, the better and
more effective will be his handling of the other prob-
lems in furthering his strategic or tactical aims.

The communication requirements of a particular
freedom of action sphere do not remain static, but vary
with the nature of the operations which the commander
undertakes. It is therefore impractical to classify
messages according to the operational functions of com-
mand, but it is rather necessary to classify them as to
(1) the administrative and operational organization of
command, and (2) the operational import of the message
itself.

The five complementary functions of a naval com-
mander are subordinate to his command function, but
situations often arise wherein the subordinate problems
are of greater operational importance than any pending
command problems. A message to a fleet unit at sea

directing it to obtain fuel and supplies at a certain
base is a logistic order with operational importance
outweighing the particular operations underway; for the
operating units are ever dependent upon their logistic
train and cannot long operate without it. But to the
logistic agency supplying the fuel, the message is of
routine administrative importance.

In general, a division may be made of communication
traffic into two categories. Messages that require some
action or movement by naval units are classed as opera-
tional traffic. Other messages, which require no action
of an operational nature, but merely notice of their con-
tents, are classed as administrative traffic. All naval
traffic can be classed, with some degree of certainty,
into one class or the other. The dividing line is not
distinct, however, and the classification is often a
question of experience and judgment rather than arbi-
trary definition. The best test is usually that of the
time element. Operational traffic is sometimes defined
as messages which require the movement of naval vessels
within a specified period of time after receipt. Thus
a movement order directing a ship to proceed from one
place to another within a few hours after receipt is
definitely an operational message, whereas a movement
order directing such movement some days in the future

may well be classed as administrative, though it may
well become operational as the day specified for the
movement approaches. Likewise, a task force commander
operating at sea may signal his night maneuvre inten-
tions some hours in advance, and the message could be
handled as administrative traffic; but the same orders
when issued minutes ahead of execution become opera-
tional traffic of the most urgent tactical nature. It
is this tendency of messages to change classification
with time that makes naval systems design difficult to
analyze when determining channel allocations and trans-
mission priority. It is advantageous to segregate ad-
ministrative and operational traffic for separate
handling, but the segregation is at best impermanent
and imperfect.

The traffic pattern is but partially determined by
the above considerations. The communication channels
should follow the command organization, for the normal
flow of information and command is from superior to
subordinate, with frequent intercourse between coordi-
nate levels of command. The naval establishment is
organized with a predominant line structure exercising
command vertically through successive echelons expand-
ing downward. There is a collateral horizontal staff
function of specializations, such as logistics,

medicine, technical engineering, legal matters, etc. which serve as service adjuncts to the line function. The naval organization is too complex to be dismissed in two lines, though these features are salient. There are vertical lines of administrative responsibility within the staff functions but the interchange of information is carried on through the line function as far as communications systems are concerned, for it is impractical to provide separate channels for the command function and for each of the staff functions.

There is no published study of naval communication traffic as to the organizational pattern with a break down as to relative importance. But even though we cannot make any quantitative conclusions as to the traffic pattern, it is possible to make some general qualitative remarks as to naval traffic.

Traffic usually follows the operational line of command, rather than the administrative line. In peacetime operations, the operational and administrative lines of command usually coincide, but in wartime it is rare that the operational line is the same as the administrative line, for the operating task forces are organized on a functional rather than administrative or type basis. It has been mentioned that administrative traffic is usually not as pressing in time as is opera-

tional traffic, and therefore such traffic is often handled by systems of communication other than radio; i.e. mail, messenger, etc. Thus the communication system will handle operational traffic in a preponderate proportion to the administrative traffic. This places a requirement of flexibility upon the system design, for the operational organization of a naval force is fluid and subject to rapid change.

As to the import of the message itself, messages fall into two classes which have been described as operational and administrative, (applying to the nature of the message itself apart from the command origin). It has been mentioned that the division is usually made on a time basis, so that messages classed as operational are of higher priority in transmission than administrative messages. There is also a difference in the internal message structure. Operational messages are usually short, peremptory commands giving specific instructions or information and requiring definite action or prompt reply in acknowledgement. Administrative messages are usually longer in nature, setting forth ideas in some detail, and not requiring immediate reply. Operational traffic cannot generally wait upon administrative traffic and the two should be kept in separate channels of communications.

There is one other consideration involved in an analysis of system organization. It has been determined that there should be two channels of communications following the chain of operational command. These channels should not extend through the entire chain of command from the highest echelon to the lowest element, for it is undesirable to have all messages delivered to all echelons indiscriminately for two reasons. First, each channel could then handle but one message at a time, and secondly, it may not be desirable, from a privacy and organizational viewpoint, to make all the information contained in all the messages available to all the echelons. On the other hand, it is equally undesirable to transmit messages from a higher echelon to a lower echelon without passing through the intermediate levels of command. The channels, therefore, must not be continuous, but must consist of discrete links which may be joined or disconnected at will to form the particular distribution desired. The manner of connecting these links and controlling them is a technical matter which will be discussed somewhat later. It is sufficient for the present to point out that such an organizational separation can be made on a switching basis to permit the naval commander to establish channels to any part of his command, or to all of it, as desired.

Likewise, channels to coordinate commands can be made integral with the common superior commander so that he is always kept informed of the lateral traffic within the command.

2. Theory of Communications Networks

It is desirable to consider some of the general aspects of the basic technical nature of communications as applied to naval communications before proceeding with detailed consideration of the component details.

Communications is basically intercourse between people by means of words, letters, pictures, etc. to convey ideas or information between individuals or groups. Of the five human senses, only the sense of hearing and the sense of sight are normally employed for communication purposes. Until modern times, communications could only be carried on directly; either vis-a-vis orally or by direct visual signals or messages. These forms of communications might be classed as sensory; that is, detectable by the human senses. But when physical barriers prevent direct sensory communications, resort must be made to some other means of intercourse which are necessarily extra-sensory. Modern technology has provided the extra-sensory communication media by which the physical barriers of distance or

intervening obstacles may be overcome. The sensory
matter is translated into the extra-sensory medium,
transmitted over all barriers, received and then re-
translated into the original sense. A consideration of
the available extra-sensory transmission media indi-
cates that the electro-magnetic wave is the most prom-
ising of all the possibilities. They may be listed in
order of merit.

1. Radio.
2. Metallic wire.
3. Modualted light.
4. Infra-red radiation.
5. Ultra-sonics.

Metallic wire systems are generally not applicable in
naval systems as the major link, but are used extensive-
ly in shore nets, and as auxiliary circuits on ship
board. The three subsequent media suffer handicaps of
various degrees which preclude their use as primary
systems although they can still be used as adjuncts in
special circumstances. Their greatest limitation is
that of adequate range, which is the greatest asset of
radio as a transmission medium. The remainder of this
paper will discuss the technical aspects of radio only
as a transmission medium in naval communication systems.

It appears that a communication channel is really
a sort of pipeline into which intelligence, in familiar
sensory forms, is placed, carried over all the barriers

of space and distance, and delivered to the addressee
in the same sensory form in which it was transmitted.
It provides, in its highest concept, an extension in
space to the radius of normal human intercourse. But
practically, and undesirably, it also introduces an ex-
tension in time as well; that is, intelligence is
delivered, not instantly as in direct intercourse, but
after an appreciable delay in time. This delay is not
directly attributable to the extra-sensory link itself,
but to the processes attendant to preparing that link,
preparing the intelligence into special forms required
by the particular type of transmission, and upon recep-
tion and distribution at the receiving station. In set-
ting the channel up for transmission, contact must be
established with the desired addressee, the circuit
tested, and procedure agreed upon. Then the message
must be filed, transcribed, released, coded, checked,
and finally transmitted with similar procedures obtain-
ing at the receiving end.

This distortion in time is not present in direct
forms of communications and represents an undesired ab-
eration in the communication channel to be eliminated.
It has been pointed out that this aberation occurs, not
because of any inherent insufficiency of the extra-
sensory portion of the channel, for traffic in this

portion of the channel moves with the speed of light.
The delay is caused rather by the mismatch of the channel
terminations to the extra-sensory link. There is, so
to speak, an "insertion loss" at the points where the
extra-sensory (radio) link joins to the human terminal
link. This mismatch represents the different capabil-
ities of the two parts of the man-machine combination.
The machine is capable of super-human speeds in trans-
mission and performance of complex operations, but the
combination must be slowed to a speed consistent with
the abilities of the human component. As in any trans-
mission problem, the solution is to remove the mismatch;
in this case, to extend the machine portion of the com-
bination to replace the human elements. The channel
should extend directly from the originator all the way
to the addressee(s).

The next step in the analysis is, then, to examine
the technical aspects of extending the machine to this
end. Such an extension is not a simple matter for the
machine lacks the one major asset of the human, the
ability to think and reason. The human can act accord-
ing to advance knowledge of a situation and according
to the reasoned dictates of the particular situation.
The machine can only respond to a set of orders <u>after</u>
the receipt of the orders, and even then only within the

framework of the designed functions of the machine. For this reason, the machine must be built, in each case, to the particular requirements of the communication system it is to serve. The next sections will deal with the basic building blocks of system design.

III COMMUNICATION CIRCUITS

The rule has been stated that a communication channel should in no way impede the free interchange of intelligence among the several widely separated parties to that channel. Strictly interpreted, this means that the channel must be operated in full duplex with facilities for multipling the connections. As will be seen, such a system is inherently extravagant of equipment and frequency spectrum, and, as a practical matter, it is desirable to approximate this degree of service by systems less extravagant and expensive. The degree to which this approximation may be carried, and still provide a satisfactory system, is a function of the type of service to be carried by the system.

The circuit of Figure 1(a) represents the simplest of all communication circuits. It is essentially a broadcast system wherein all traffic is transmitted "blind" and received by all the parties to the circuit without receipt or acknowledgement. It is easily con-

nected in multiple, and requires little equipment. Its chief disadvantage as a system is that it provides no reverse channel of communication.

The next obvious step is to provide a reverse channel in parallel to the one-way channel and thus form a two-way channel. Figure 1(b) illustrates such a circuit. This is a 4-wire full duplex circuit and is the normal circuit for point-to-point radio circuits in both commercial and military shore installations. Traffic is sent in both directions simultaneously when used for telegraph circuits, or the terminations may be reduced to a 2-wire circuit and used for full duplex telephony. In fleet radio nets, the two-way circuit is more often operated with both channels on the same frequency, for this circuit cannot be operated in multiple without an excessive amount of equipment. The circuit then operates on a half duplex basis but with the possibility of employing break-in procedure. To operate a system in this manner requires a human agency at the terminating ends, for a machine cannot be built with the discriminating qualities of the human ear.

A more exhaustive examination of the drawbacks of a 4-wire circuit is warranted for a radio net is inherently and inescapably a 4-wire system and cannot be
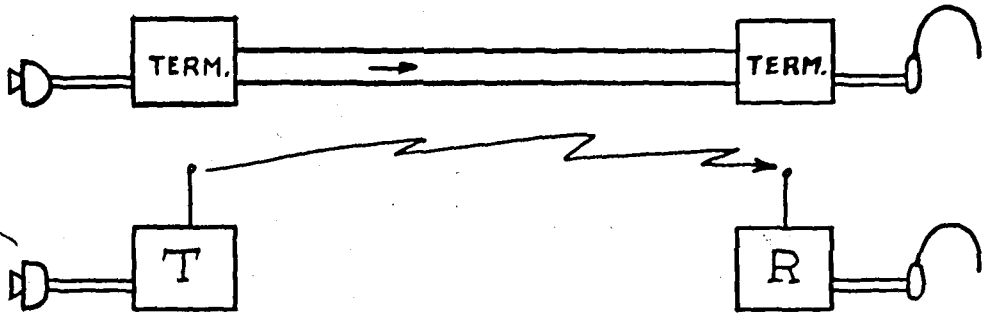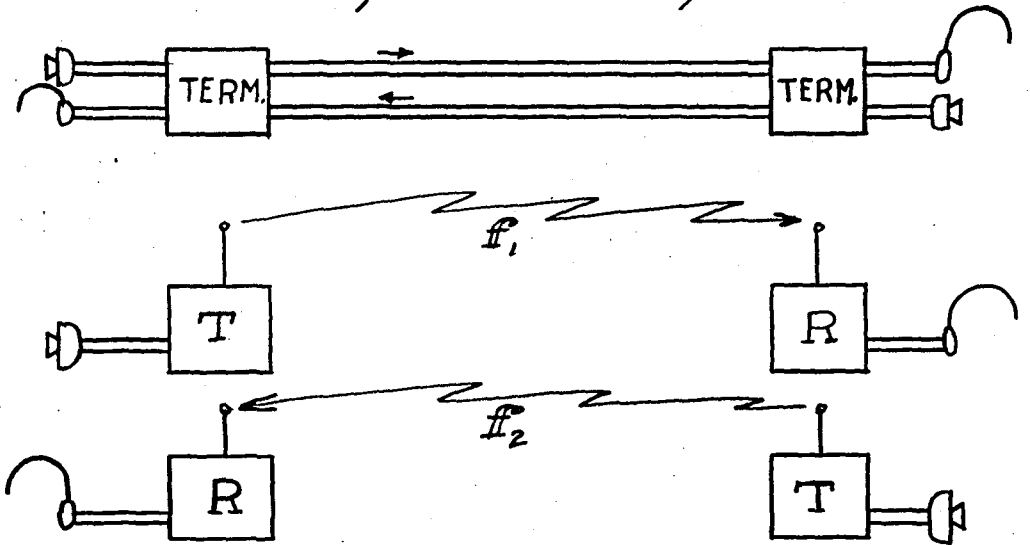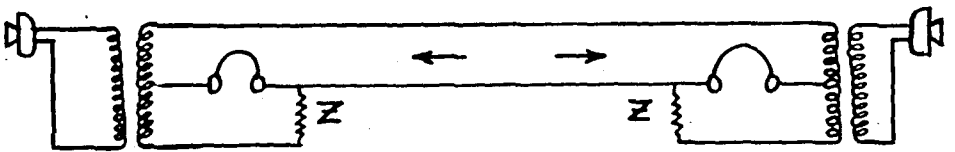
Fig. 1 (a) "One way" Circuit.

Fig. 1 (b) 4-wire circuit.

NO EQUIVALENT
RADIO CIRCUIT.

Fig. 1 (c) 2-wire circuit.

reduced to a 2-wire circuit by any such means as serve
when using metallic wire circuits. Figure 1(c) shows
a 2-wire metallic circuit for which there is no equi-
valent radio circuit. This circuit is not actually
used in wire plants for this purpose but represents the
basic idea of reduction of a 4-wire circuit to two met-
tallic conductors. In wire plants, the capital outlay
in the outside wire plant would be exhorbitant if some
such reduction were not possible for not only would all
loops have to be run with four conducting wires, but
the switching problem in the terminals would be quite
complicated. In the 2-wire circuit, the system is still
operated in full duplex, but the problems of trunking,
switching and multiple connections are greatly simpli-
fied at a great saving in equipment and money.

In this circuit, (Figure 1(c)) the anti-sidetone
coils act as directional couplers at each station. The
degree of R-W channel crosstalk is a function of the
balance and return loss of the impedance net Z. This
net, for zero cross channel coupling, must exactly
match the line impedance both as to magnitude and phase
at all transmission frequencies. It is not too diffi-
cult to obtain an impedance network of this kind which
will perform satisfactorily at voice frequencies on
wire lines, but as the frequency goes up, it is

increasingly difficult to obtain the requisite degree
of match, and is nearly impossible to perform at radio
frequencies, although some progress is being made
towards this end in the microwave region.

On wire lines, the differential in power levels on
the send and receive channels at one station amounts to
only a few db so that the return loss of the direction-
al coupler need only be 20 or 30 db for satisfactory
service. In radio, because of its low transmission ef-
ficiency as compared to a wire line, this power diffi-
rential is of the order of 120-150 db and the return
loss of the directional coupler for radio work would
have to be 150 db or more to give adequate freedom from
cross-channel modualtion. Such a loss is unobtainable
at present though the dividends in research and develop-
ment of such a de-coupler will be tremendous. It would
then be possible to bring to radio all the flexibility
of wire circuits, using the same frequency for both
transmitting and receiving in full duplex on the same
antenna. Until such a device is developed, it is neces-
sary to develop the radio system design according to
the principles of 4-wire circuitry.

A 4-wire mettalic circuit can be easily developed
and built with full switching and multiple facilities.

Figure 1(d) illustrates the basic switch plan for just
four 4-wire tandem connected circuits which are to be
so arranged that any two may connect without hindering
the operation of the other circuits, or three or more
circuits may be connected in multiple with full duplex.
All parties on such a circuit may freely converse ex-
actly as though they were all gathered together in one
place. Actually, full duplex is defined as a system
which will allow transmission and receiption of messages
over a circuit simultaneously. When a 4-wire two
station circuit is multiped with a third station, the
circuit losses its full duplex characteristic, for the
two directions lose identity at the third station and
will mutually interfere. This represents no handicap
for voice communications for it is entirely within the
realm of ordinary human experience that a third person
can understand nothing if two other people are shouting
at one another and it is ordinarily expected that only
one person shall talk at a time. This difficulty could
be overcome by use of multiplex principles with fre-
quency separation of the channel directions, or by
direct trunking, but in either case the expense would
be incommensurate with the returns.

On the switch frame of Figure 1(d), the number of
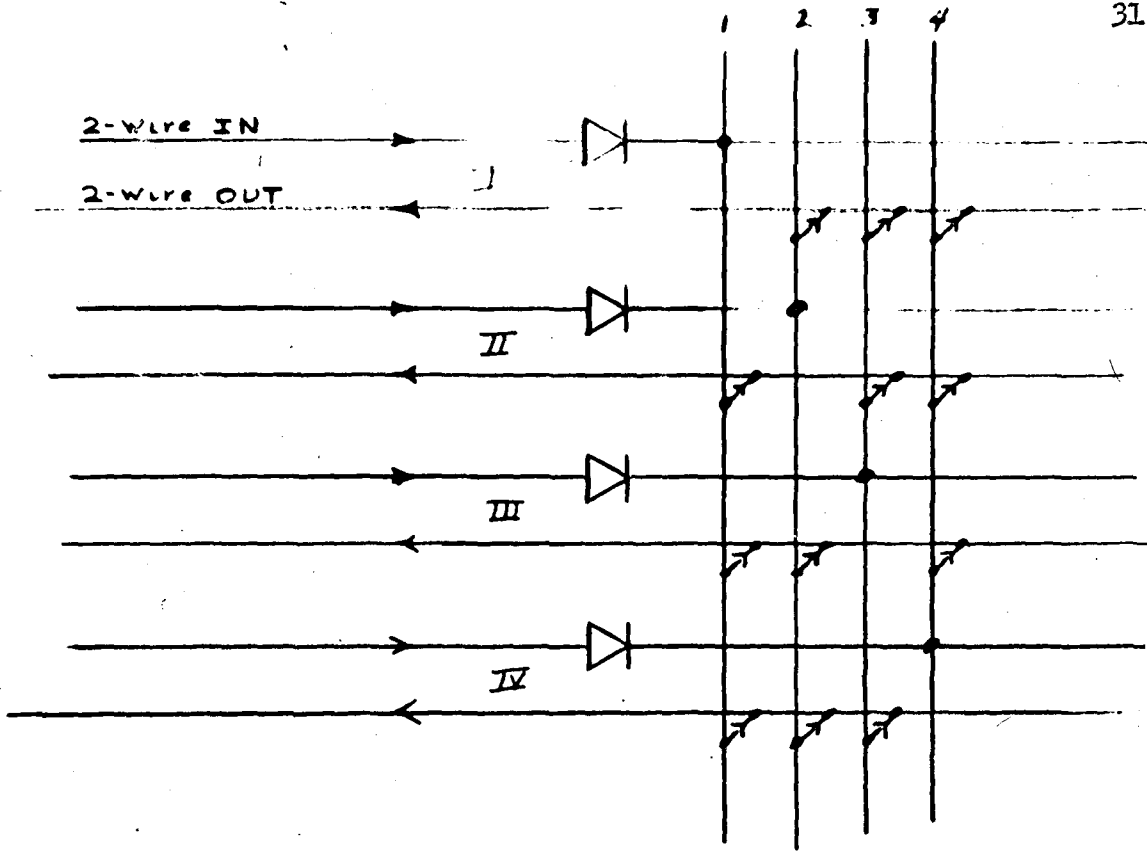switch operations required to complete a call is:

Fig.1 Four wire switching plan.

Fig.1(e) Switch chart.

$$S = \frac{n!}{(n-2)!}$$

where $\underline{n}$ is number of stations required to be interconnected. It is readily evident that the number of operations mounts to astronomical proportions with even moderate multiple demands and the problem of actually building a switch board of this type would be most difficult.

For every switch that is closed, its conjugate on the switch chart (Figure 1(e)) must also be closed. When several circuits are to be interconnected, all switch points having the desired channel numbers for both digits must be closed. Thus, if channel I is to be connected to channel II, switch points 12 and 21 must be closed. If channels I, II, and III are to be interconnected, then switchpoints 12, 21, 13, 31, 23, and 32 must be closed. If one hundred stations are to be interconnected, 9900 switch operations are necessary.

To generalize the switch frame into a radio net, it is necessary merely to note that each tie point on the crossbars is equivalent to a radio transmitter, each switch point is equivalent to a radio receiver, and each vertical bus represents a separate operating frequency for the network. Thus, for a four station radio net operating in full duplex, there must be a

separate frequency for each station of the net, requir-
ing four transmitters and twelve receivers. This is
rather more equipment than is ordinarily justifiable
for just four stations and, unless the requirements of
the communication service between them justified this
great outlay in equipment and monopoly of spectrum,
some compromise mode of system operation can usually be
found less demanding of equipment.

There is one interesting feature to be noted. The
radio net is truly full duplex in operation and does
not suffer the limitation of the equivalent metallic
wire set. Traffic may be sent simultaneously between
all stations without any limitations of interference.
This is one of the advantages of radio nets; that the
very nature of radio is a frequency discriminating
principle which in itself constitutes a vast directly
trunked system. Thus the equivalent to a new wire line
can be established by a mere twist of the dial. Whereas
in a wire plant, the cost of erecting and maintaining
a wire line may be considerable, the radio line is
"wire-less" and costs nothing. The discussion is now
trespassing upon that region reserved for a later sec-
tion and will be developed more fully in the consider-
ation of trunking problems.

There are a number of ways in which the size and

expense of a 4-wire radio net may be avoided and yet retain most of the advantages.

One method is the familiar push-to-talk procedure of the police, airway, and military nets. This is a half duplex system; for messages can be transmitted in but one direction at a time. To reverse the direction of traffic it is necessary to alter the circuit configuration by a positive action of the operator. This system is very economical of equipment and frequencies but at a sacrifice to traffic handling capacity. In a true full duplex system operating on a 4-wire basis, the amount of traffic handled at any one station in the net (the total of incoming and outgoing messages) is equal to the number of stations in the net. In the push-to-talk system, the net can handle but one message at a time, for all stations share a common frequency.

The push-to-talk circuit is the nearest equivalent to 2-wire metallic net that exists in radio. The decoupling function of the hybrid coil is replaced by a transfer relay which alternately connects first the receiver and then the transmitter according to the will of the operator. It thus has most of the advantages of 2-wire systems with two very important drawbacks. First, when a station is transmitting, it cannot receive

too, and there is no way of breaking in on a circuit
until the sending station releases it. Second, the op-
eration of the transfer relay by a push-button is in-
convenient and awkward. There are systems whereby the
transfer is accomplished by voice operated devices
which automatically transfer the send-receive function
when a speaker starts to talk. These systems are so
large and clumsy that they are generally not used if it
can be avoided. But in all other respects, the push-
to-talk technique offers all the advantages of connec-
ting simplicity and economy inherent in the 2-wire
system. The traffic handling characteristic could be
improved by use of high speed telegraphy, or by provid-
ing multiple independent channels.

The TDZ-RDZ UHF equipment represents an attempt
to improve the traffic capacity of the push-to-talk
circuit by the provision of a number of separate chan-
nels which may be selected optionally by a dial selector
device. While such a system will improve the overall
network capacity, it is really little better than a
single channel system as far as the individual stations
are concerned; for they still have but one traffic
carrying channel available at a time, (unless, of
course, equipment is duplicated, in which case the
system loses its economic advantage). If, within a

given net, all traffic is equally distributed amont the
stations, both as to sending and receiving, this method
of increasing traffic capacity will be satisfactory;
but as soon as the circuit becomes unbalanced and all
traffic tends to gravitate towards one particular sta-
tion, all the advantage of multichannel operation are
lost. Thus if within a ten station net, five of the
stations originate traffic addressed, one each, to the
other five stations, the traffic may be cleared simul-
taneously on five different channels. But if nine of
the stations all originate traffic addressed to the one
remaining station, the net might just as well have but
one channel. The difficulty is, of course, that the
TDZ-RDZ equipment has ten channels available which are
mutually exclusive, while what is needed to improve the
push-to-talk traffic capacity is to have all channels
available simultaneously to all stations. This involves
consideration of an adequate terminal system to control
the net, for the problem of coordinating and control-
ling the communication activity of, say, thirty
stations on ten different channels would be of super-
human proportions.

With but little design effort and slight expense,
the control and circuit discipline features of commun-
ication system can be built directly into the system.

It takes experienced, well trained personnel to maintain circuit discipline on a crowded heavily loaded circuit. If instead of depending on human discipline and training to maintain order on the network, the equipment is so designed that a communication error cannot be made by the operating personnel, a large step will have been taken towards eliminating the need for trained personnel. It must constantly be borne in mind that one of the major aims of system design is to permit the operation of the system by inexperienced personnel with little communication background. The system must be so simple that any tyro can operate it, yet at the same time it must be foolproof so as not to upset the system in case of error.

It may be argued that manpower is cheap and there is no need to design expensive automatic equipment to do that which anybody can learn to do with time. We have paid the price for that attitude in the past with snarled communications, lost traffic, and ineffective operations. There are times when a message is of no use if it cannot be sent in seconds, and there is no time then to hunt for channels or beg for priority. The equipment must be inherently able to find or create a clear channel whenever needed, and only a machine can do it fast enough.

The TBS was the workhorse equipment of the past war and did yeoman duty as a fleet tactical circuit. It had, however, two glaring faults, not from the equipment design viewpoint, but from the system design aspect. The transmitter was, in the normal idle condition, completely deenergized and required about thirty seconds warm-up before it could be used. This delay proved unacceptible under operating conditions and the transmitter was often kept in continuous standby, a condition for which the equipment was not designed, with subsequent maintenance troubles in the power units. A design alteration was finally made which allowed instant operation without warm-up. A more serious defect was the absence of lock-out to prevent interference by undisciplined transmissions. When two stations are transmitting on a push-to-talk net, neither station is monitering the transmission and is thus not aware of the interference. The result is that both transmissions are mutually garbled. The answer is lockout device which will not allow more than one station on the air at a time. Even in very urgent cases, it is usually less confusing to allow current traffic to be completed rather than trying to interrupt the traffic. In a push-to-talk circuit, there is no hope of interrupting existing traffic anyway so it would be
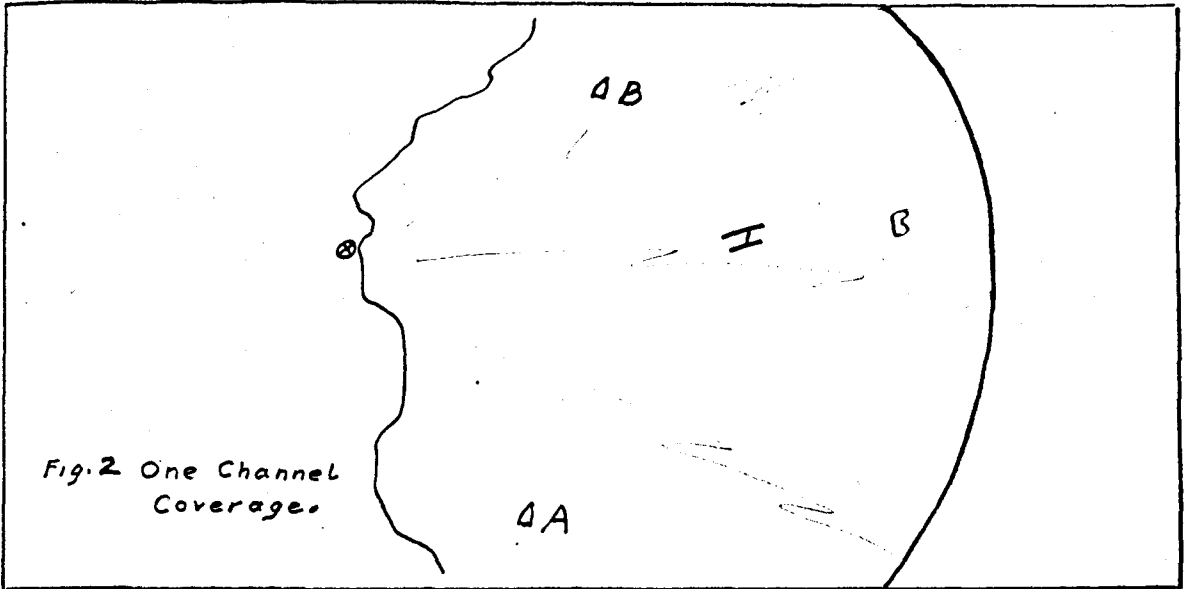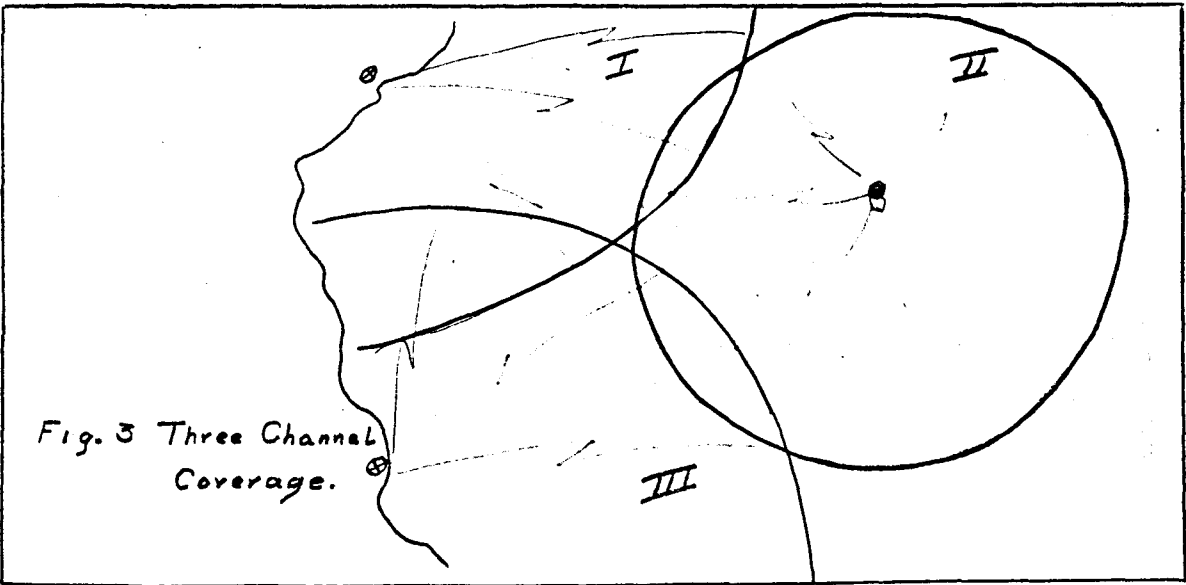
Fig. 2 One Channel Coverage.

Fig. 3 Three Channel Coverage.
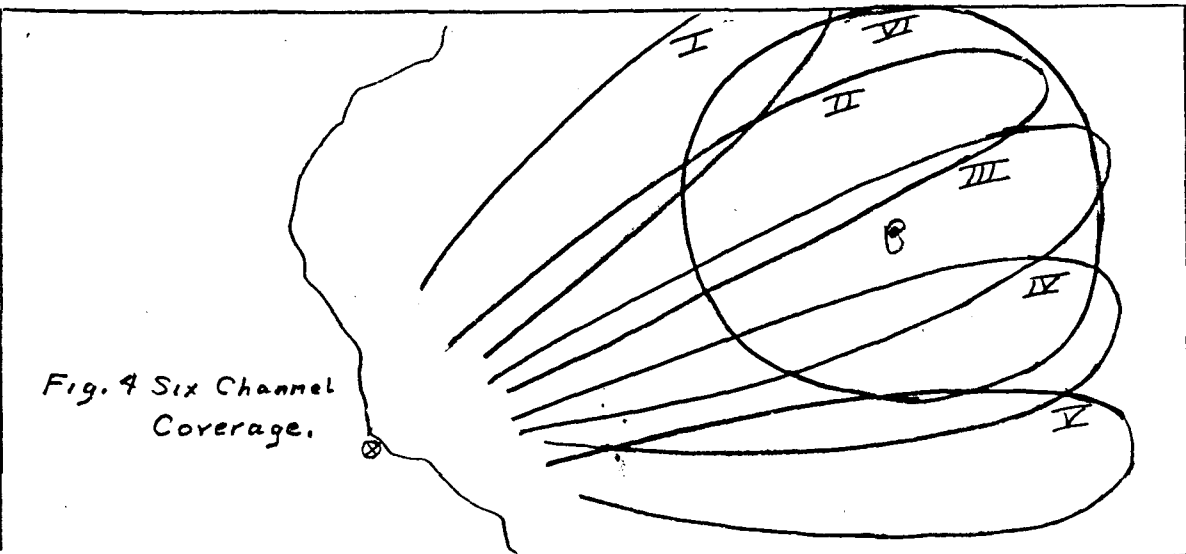
Fig. 4 Six Channel Coverage.

far better to prevent destruction of that traffic by attempts to break-in. Such a device was never built into the TBS system although its inclusion would have been a very simple matter.

The simplest type of communication net is the broadcast network. The transmitting station sends "one-way" without requiring or waiting for answer or acknowledgement. Figure 2 illustrates the simplest feature of a broadcast system. Since only one transmitter is used, the entire area is covered by but one channel, and station A must share the same incoming channel with stations B and C. This means that station A must guard and copy all traffic, even that addressed to B or C, in order not to miss any traffic addressed to A. This represents waste time as far as A is concerned, both in man power and equipment, and should be eliminated. Figure 3 illustrates three channel coverage of the same area wherein three low power stations handle the traffic on a basis of geographic distribution of addressees. This method may be termed as space channeling, for the stations are widely separated and may (or may not) operate on the same common frequency. With this coverage the three receiving stations will receive only traffic addressed to them and the system capacity is tripled.

If the transmitting stations are geographically separated and operate on separate frequency channels as well, generous overlap may be established giving complete coverage to a large area of mobile operations. The mobile stations now need to change frequency as they pass from one area to another, but this is no great handicap. The principles of space channeling and frequency channeling could be carried out <u>reductio ad absurdum</u> to the extent that each little area will have a separate channel for traffic delivery and no station will ever receive traffic not addressed to it. Figure 4 represents six channels covering the same are of Figure 2 giving a sixfold traffic capacity to the system.

There are definite tactical and strategic drawbacks to multichannel broadcast systems. First, space channeling will, by methods of traffic analysis, reveal the geographic distribution of the mobile units. Secondly, frequency channeling, will reveal the operational organization of the mobile units. (Assuming that the frequency channels are assigned on an organizational basis.) It could equally be argued that, with modern methods of reconnaisance and intelligence, these matters are not secure from enemy detection anyway. Nevertheless, there is no need to make it easier for the enemy to determine these matters and some basis for channeling

which would conceal these facts should be devised. The possibilities of greater traffic handling as against the possible disadvantages of decreased security must be balanced. With judicial design and operation there should be no loss of security involved and the advantages will far outweigh the disadvantages.

One basic principle of systems design is here illustrated. From the economy and security viewpoint, one centrally located powerful station is the best for broadcast service. From the aspect of traffic capacity and speed, numerous small low powered stations are required. The two are not reconcilable except on a compromise basis. This basic principle is equally applicable in other services but not so readily evident.

The greatest volume of traffic, both commercially and militarily, is carried in point-to-point networks. Such circuits are established under very stable operating conditions and are ideally suited to the employment of all the technical tools available to the communications engineer.

With the outbreak of war, the point-to-point naval communication net was the first to feel the weight of the growing traffic, for all fleet and shore establishment traffic eventually passes through some point-to-

point trunk for ultimate delivery. Consequently, the
point-to-point nets received the full attention of the
communications experts while the fleet communication
problem went begging. There are no particularly diffi-
cult system problems in point-to-point communications and
it offers the greatest scope to the engineer in multi-
plex and high speed techniques. The greatest problems
involve trunking patterns and channel efficiency.

When it becomes necessary to provide connections
between many stations, there are but two ways these con-
nections can be made; either direct or in tandem. Fig-
ure 5 demonstrates the large number of trunk connections
needed for direct trunking. Figure 6 illustrates the
alternative form of trunking wherein all stations are
switched through a central control station C. In prac-
tice, a combination of direct and tandem trunking is
employed in conformity with a General Switch Plan based
on study of traffic experience. In general, large
centrals having large volumes of traffic are directly
trunked and the smaller centrals required to tandem
connect through the larger ones.

The tandem net has the advantage of employing a
fewer number of more efficient trunks, but suffers in
that traffic at the central station is in competition
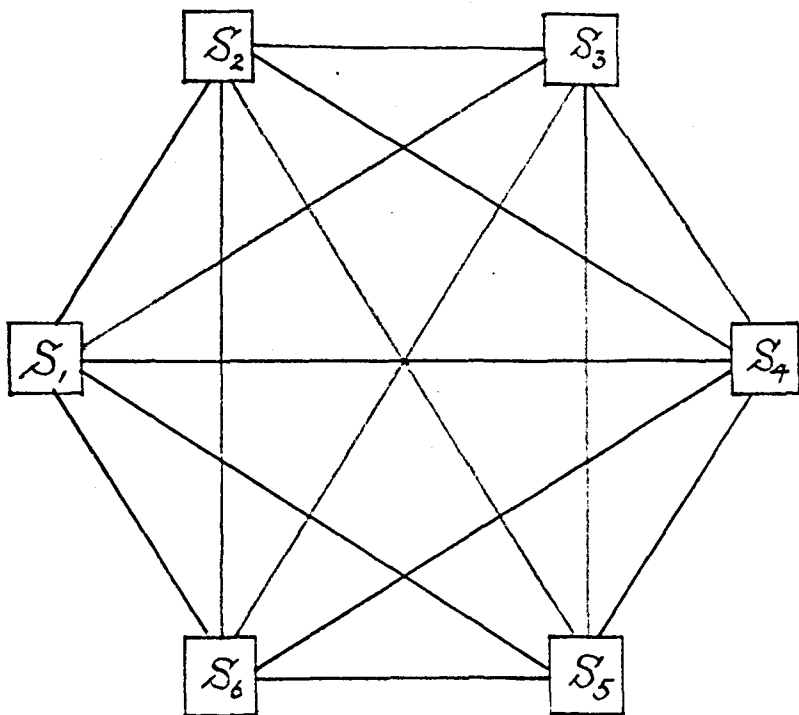
Fig. 5 Direct Net
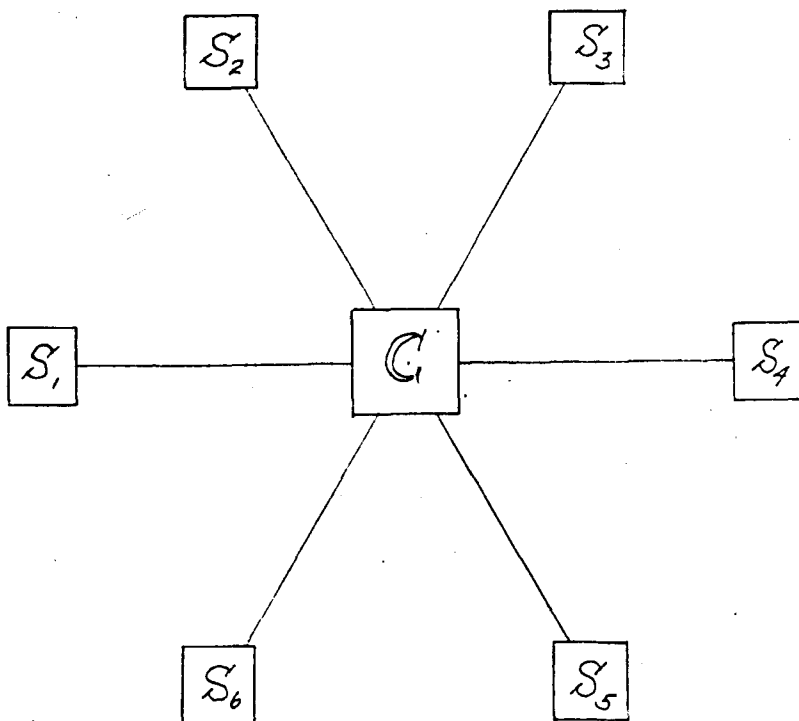
Fig. 6 Tandem Net

for any particular trunk which reduces the traffic
handling ability of the system. Also each station is
entirely dependent upon one trunk line, which, if des-
troyed, will isolate that station from the net. A
direct net is more expensive but has the advantage of
greater traffic capacity than a tandem net. It has been
pointed out that a radio net is inherently a directly
connected system for it costs nothing to broadcast to
several stations at once, whereas in the equivalent
wire net, each station must be connected with a separate
pair of metallic conductors. Thus a radio net can en-
joy all the advantages of direct trunking without the
added cost to the outside plant, and the tandem trunk
possibilities can be reserved for relay communications.

There is a definite limit to the number of times
a circuit may be tandem trunked without excessive de-
gradation, unless the intelligence can be regenerated
in the tandem central. Each connection of the cir-
cuit will add a certain amount of noise to the circuit
until finally the signal-to-noise ratio will be un-
acceptable. Generally, if the overall circuit loss
exceeds 30 db, the circuit merit will become marginal,
and this determines, in conjunction with the loss per
connection, the number of connections that may be made.

Provisions for relay connection require the most

rigid overall engineering standards, for all circuits
must be able to interconnect without reacting adversely
on the other connections in the circuit. A circuit
from $\underline{A}$ to $\underline{B}$ may be entirely satisfactory, and likewise
for a loop from $\underline{B}$ to $\underline{C}$, but, unless overall engineering
standards of a high quality are maintained over the en-
tire system, a tandem connection of $\underline{A}$ to $\underline{C}$ through $\underline{B}$
may be unacceptable.

If noise considerations determine that the maximum
tandem loss cannot exceed 30 db, and it is desired that
it should be possible to make four tandem connections,
the loss of each trunk cannot exceed 6 db. Thus in any
relay net, the quality of each trunk must far exceed the
permissable standard of the overall relay, both as to
bandwidth and loss. And further, these standards will
have to be maintained with unrelenting attention
throughout the network, for if even one part of the
circuit is substandard, the entire connection will be
rendered unacceptable.

Figures 7, 8, 9, 10, and 11 are self evident il-
lustrations of radio nets employing various trunk plans.
Figure 7 represents the plan of the common push-to-talk
net with several channels available common to all the
stations. Figure 8 is a full duplex circuit. Note that
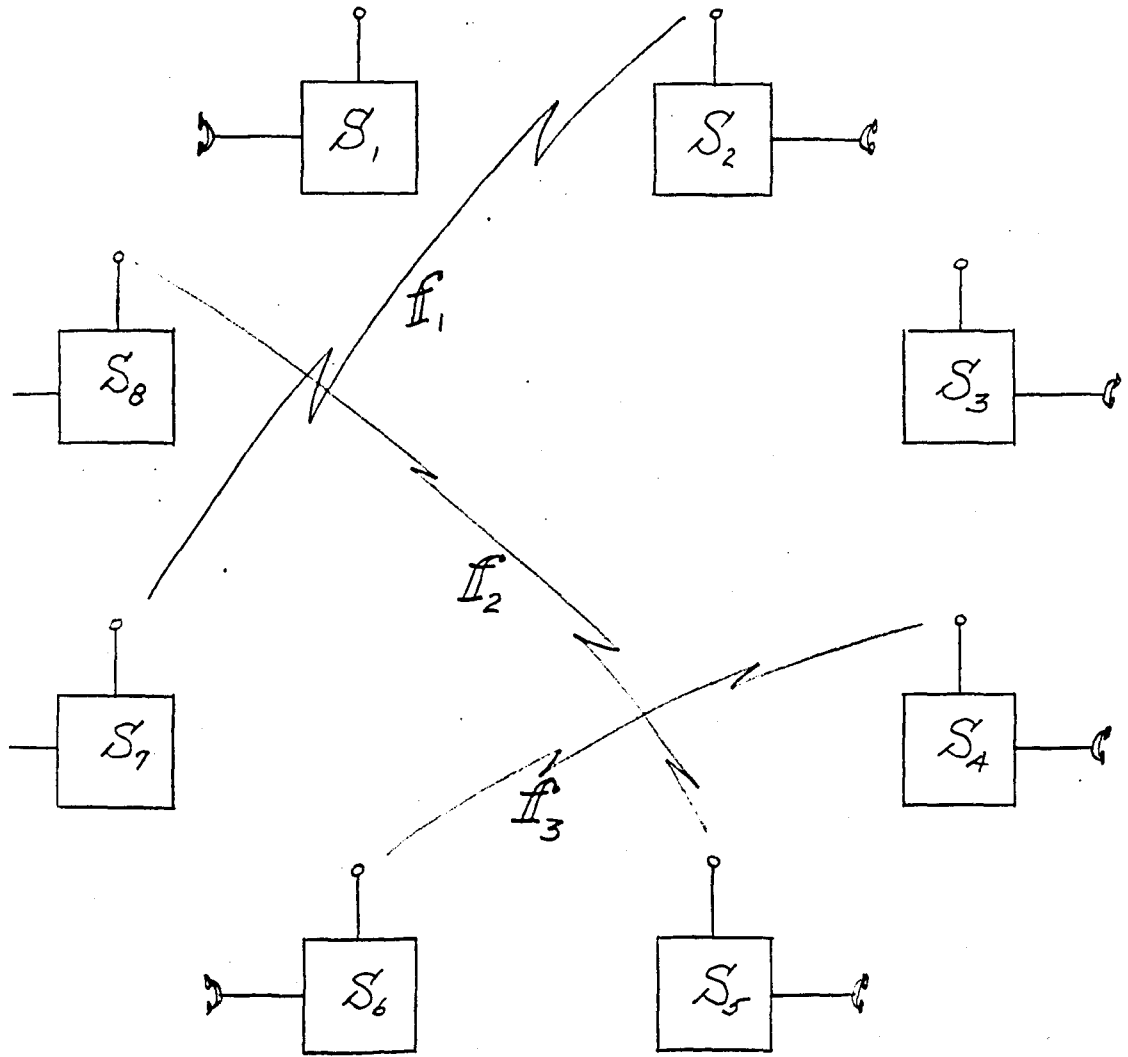
FIG. 7   Direct Radio Net.
HALF DUPLEX
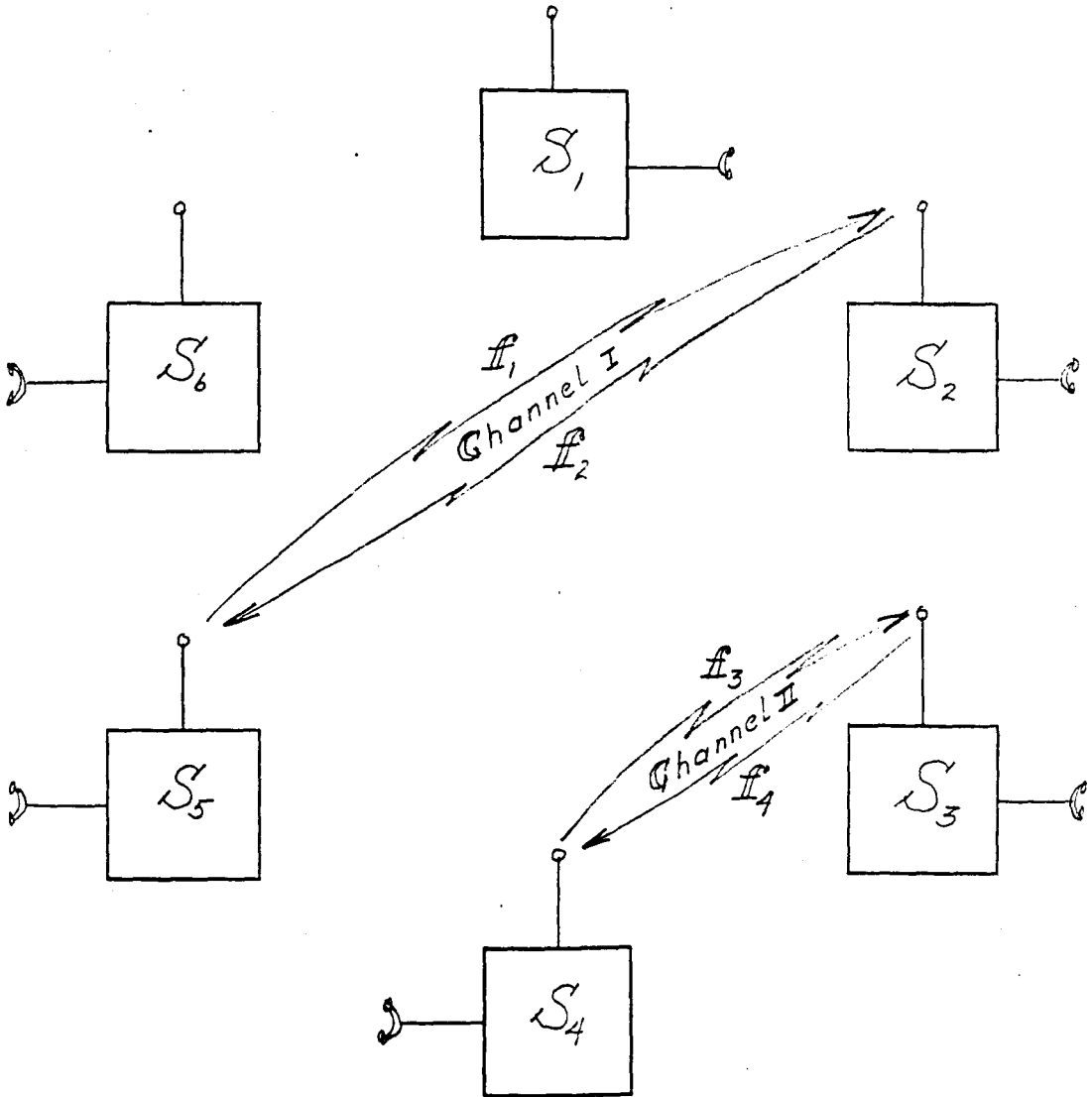
FIG. 8   Direct Radio Net.
FULL DUPLEX
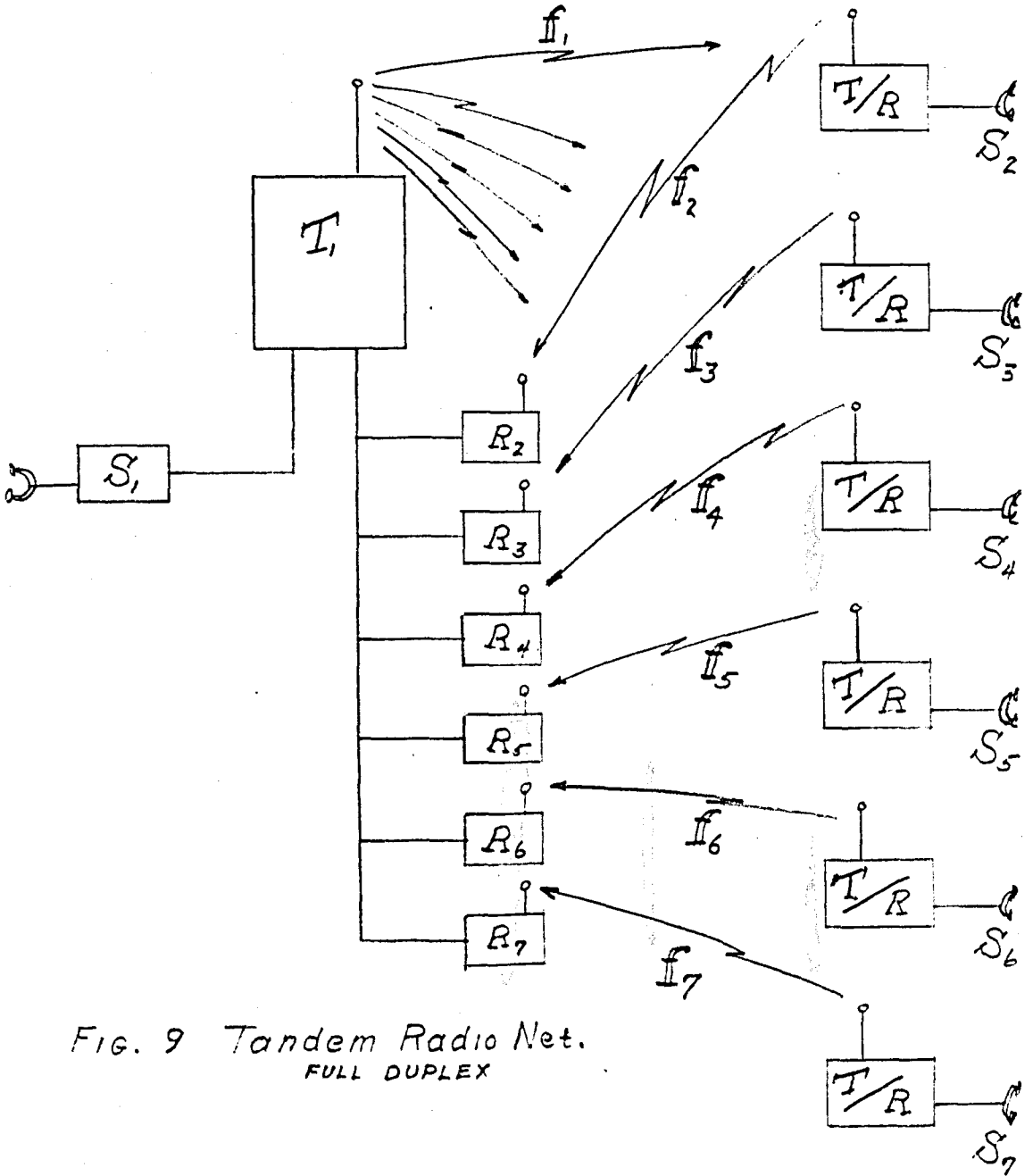
FIG. 9 Tandem Radio Net.
FULL DUPLEX
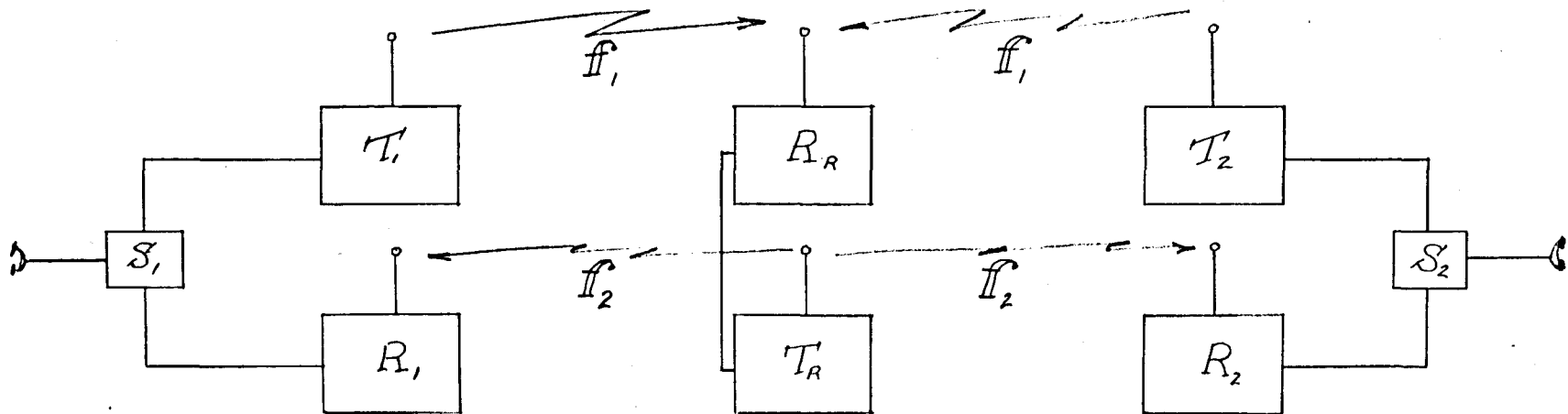
Fig. 10   Single Station Relay.
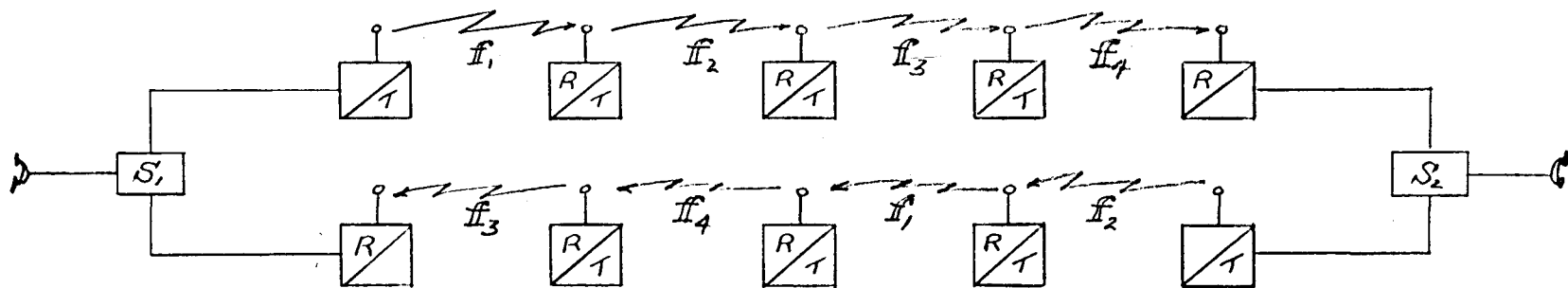
Fig. 11   Multiple Station Relay.

there must be as many frequencies employed as there are
stations in operation, if there is to be no mutual in-
terference. Figure 9 shows a tandem radio net in full
duplex. Again note that there are as many frequencies
employed as there are stations in the net, although
here there is but one channel. It is inherent and
axiomatic that there must be as many frequencies employ-
ed in full duplex operation as there are stations to be
served.

Figure 10 is a single station relay net. It cannot
be extended any further than as shown, and if a further
system extension is required, it must be obtained by
some such relay system as Figure 11, (although it may be
extended by connecting S_2 to another link employing two
other frequencies.)

After this elementary consideration of communica-
tion circuits, it is time to consider some of the more
detailed technical aspects of Systems Engineering.

IV   SYSTEMS ENGINEERING

Systems engineering divides naturally into two
major provinces; those of transmission engineering and
of switch engineering. The former has as its field all
the considerations of traffic, trunking, line levels,
amplifier gains and circuit losses, crosstalk, multiplex

operations, etc. or in short, all the forces that <u>move</u>
traffic in the communication network. Switching must
arrange for signalling, selection, controlling, super-
vising, guarding, and all the functions which <u>guide</u>
traffic in the system. The concept of transmission is
familiar to anyone connected with radio communications,
but the concept of switching is one that has grown
almost entirely from the art of telephony. The tele-
phone companies early realized that to make the tele-
phone economically feasible it must be so simple as to
require no experience or technical training to operate
it, and it must be so inexpensive that everyone could
afford to use it. The problem of switching is inherent
in the telephone system, and if it were to be done on
an entirely manual basis, the operating staff would be
so large as to make the cost incommensurate to the qual-
ity of service that could be rendered. The cost aspect
was early understood and the invention of the automatic
telephone switch system followed that of the telephone
itself by only three years.

This paper is basically concerned with the idea
that systems engineering has not been fully exploited
and applied to naval communications, particularly the
aspects of controlled selection and switching, and auto-
matic traffic handling in fleet circuits.

1. Transmission

The most fundamental problem of radio communications is that of propogation and reliable range. The definition of reliable range is necessarily an arbitrary one for it is dependent upon what is considered a satisfactory signal level. At a given range, an adequate signal level for one type of service or equipment may be entirely inadequate for another.

The characteristics of radio propogation are well known and voluminous data have been obtained on propogation at nearly all frequencies. For purposes of system design, the spectrum may be divided into three essential bands.

1. <u>Low Frequencies</u>. (1.5 mcs. and below) Basic propogation is of the ground wave which suffers but low attenuation. Range (for a given field strength) varies directly as the square root of the power and inversely to the frequency. Propogation is but little affected by ionosphere condition or solar activity. Field is remarkably steady and free from fade particularly at the very low frequencies. Noise level is highest in this band with a diurnal and seasonal variation in intensity.

2. <u>Medium and High Frequencies</u>. (1.5 - 30 mcs.)

Ground wave highly attenuated and little used except for short range low power systems. Sky-wave propogation is a complex function of frequency, inospheric condition, solar activity, relative geographical positions, etc. and relatively independent of transmitter power. The field intensity is variable with distance and subject to fade with time due to variable multipath reflections from the ionosphere.

3. <u>VHF and UHF</u> (30 mcs. and above) The propogation characteristics of the radio wave are quasi-optical and partially predictable by optical theory. The circuit coefficient is relatively independent of all variables and remains constant within the service area which is determined as a proportionate function of the optical horizon. Field strength is independent of the ionospheric condition but fade effects are sometimes experienced because of multipath reflections from the surface of the earth.

Each band is inherently better able to provide some types of service better than the other bands. The low frequencies are better able to provide long range circuits where reliability is paramount and cost considerations are secondary. The higher frequencies have

replaced the low frequencies for most of the long range point-to-point circuits because of the lower cost of the equipment and the fact that reliability can be made satisfactory by diversity reception of the skywave.

The UHF and VHF bands are in the process of exploration and exploitation and provide extremely reliable and stable service for short range systems such as police networks, mobile communication nets, and short distance substitutes for wire links. The chief advantages of this band are the high stability and large capacity of the circuits provided as against the low cost and compact size of the equipment.

The demands for radio service have so crowded the frequency spectrum that expansion has been required into the higher and higher ranges for more room. The frequency spectrum has a logarithmic structure which means that at the higher frequencies the available spectrum increases at an exponential rate. Since the spectrum demands of any particular service are independent of the operating frequency, more service channels can be provided in the same percentage band at the higher frequencies. A 1% band at 100 mcs. can carry 1000 times as much traffic as a 1% band at 100 kcs. More important, perhaps, the band width of tuned circuits is a fixed

percentage of the operating frequency. Thus the 6 mc.
bandwidth required for television is as easily obtained
at 60 mcs. as the 5kc. band required for voice at 60 kcs.,
and at 4000 mcs., we can easily put 480 voice channels
in the same percentage band width. For these reasons
the VHF - UHF bands are replacing the lower frequency
channels wherever the limited range is not a limiting
factor.

Since the range and usefullness of a circuit is
determined by its signal to noise ration, the major
problem of transmission engineering is to improve this
factor.

Radio noise may be divided into four classifica-
tions, depending on origin.

  1. Atmospheric noise.

  2. Cosmic noise.

  3. Man-made noise.

  4. Receiver and antenna noise.

Atmospheric noise is dominant below 1 mc. as a function
of time, frequency, geographic position, weather, and
season of the year. Little has been done to reduce the
effects of atmospheric noise although extensive studies
are afoot to develop noise reducing circuits. The modu-
lation systems which discriminate against atmospheric

and man-made noise are practically operable only in the regions above 10 mc. and in that region atmospheric noise is of negligible importance.

Cosmic noise originates in outer space and represents a universal noise level at about -10 db (referred to 1 uv/m). In the absence of man-made and atmospheric noise, cosmic noise represents an ultimate limit to system sensitivity.

Man-made noise is the noise of civilization generated by electrical equipment and machinery which produce noise radiation. Like industrial audio noise levels it can be reduced only by a concerted effort on the part of the designers of the offending equipment. For isolated stations, such as ships at sea, a real effort to reduce the electric noise level could pay real dividens in increased circuit merit of the communications circuits. Man-made noise is dominant in the range from 1 mc. to about 500 mc.

Receiver noise represents the internal random noise of resistors and vacuum tubes of the transmitting and receiving equipment. This represents the most fertile field for scientific design reduction of noise in communication circuits but there are theoretical limits to the amount of reduction that can be accomplished. Comparisons of actual receivers are made to an ideal receiver having noise derived only from the antenna

radiation resistance, the irreducible minimum. Noise figures for ordinarily good receivers run from 10 db. (above ideal receiver noise) in the frequency range up to 500 mcs., to 15 or 20 db. for receivers operating in the range of 1000 mcs. and above.

Noise reduction is an important aspect of systems engineering, for the one aim of system design is to obtain the best communications with the least amount of equipment. A 10 db. improvement in circuit noise figure is equivalent to increasing transmitter power by a factor of 10, a saving not to be lightly ignored. The minimum C/N ratio which produces a satisfactory communication circuit is 10 db. with a 20 or 25 db. ratio being required for good quality circuits to carry voice, facsimile, etc.

Since noise is proportional to the square root of the band width, the best circuit noise figure can be obtained with the narrow band services such as Morse telegraphy and teleprinters. For modulators requiring a greater band width, such as voice, facsimile, etc., such special systems as single or assymetric side band modulation improve the C/N ratios over double side band modulation by decreasing the band width spectrum. Since noise is generally distributed uniformally with frequency

(within any small band) and has an amplitude modulation characteristic, narrow band FM systems naturally discriminate against noise to a certain extent. The pulse modulation systems, because of the high pulse peak powers employed and the techniques of limiting and clipping offer systems which inherently give very high S/N ratios. The alternative to reducing noise is to increase the carrier (i.e. transmitter) power. It is generally less costly to reduce noise than to build and operate larger transmitters.

The next most important aspect of transmission engineering is circuit stability. As opposed to noise, which is the problem of adequate circuit quality, stability is the problem of maintaining the circuit connection and guarding against interference with or by other circuits. This is for the most part a problem of technical equipment design. Radio transmission involves the generation and radiation of electrical energy of a particualr frequency and receiving that particular frequency by a selective receiver. The stability of the circuit will be a function of the stability of the transmitting device as to frequency and power level, the efficiency of the transmitting medium, and the selectivity and frequency stability of the receiving device.

Frequency stability of both the transmitters and

receivers is determined by the technical aspects of circuit design subject to the restrictions of law and international agreement. For the purposes of establishing order in the radio spectrum, the laws define the maximum instability to be allowed in the various frequency bands but for many services greater than legal stability is required. Services that require great selectivity also require great stability for excessive frequency drift will destroy the circuit connection. The exact amount of drift to be allowed is determined by a complex consideration of side band spectrum of the transmitted signal, the selectivity characteristic of the radio receiver, and the amount of side band energy that can be lost before the intelligence contained in the side band is seriously affected. In general, the amount of drift of either the transmitter or receiver cannot exceed one quarter of the receiver selective band before the intelligence is seriously impaired and it is usually necessary to maintain stability well below this limit. Thus if the transmitted spectrum is 10 kc. wide, and the receiver has a 10 kc. band width, the transmitter and receiver would have to be maintained on frequency within about 1 kc. to maintain an adequate circuit merit. This degree of stability is more difficult to maintain the higher the operating frequency and will require a relax-

ation in the receiver selectivity in order to maintain the connection. But to widen the receiver band width is to raise the noise level at the detector. An alternative method is to provide an automatic frequency control device on the receiver so that it will follow the transmitter in frequency drift. Either method is equally feasible and the choice must be made on the basis of the quality service desired, as against the considerations of cost and size of equipment.

Aside from the problem of merely maintaining the connection, there is the more exacting problem of preventing cross channel interference due to the instability and inadequate selectivity. The problem here is self explanatory. With frequency spectrum at a premium, it is becoming increasingly important not to lose any of the spectrum to excessive guard margins on the channels. It is desirable to space the channels as closely together as is consistent with channel stability and selectivity. The consequence of instability are here more serious than in the previously considered circumstance, for it involves interference with other channels as well as the loss of own channel. Once a channel allotment has been determined, it is imperative that the operating channels remain within their assigned frequency band.

When operating a multipoint net, stability is a
very serious consideration. If one transmitter is send-
ing to several receivers, all receivers must be kept on
frequency with the transmitter, a more difficult problem
than in direct point-to-point nets. In fact, stability
has a very great bearing on the reliability of the cir-
cuit for naval communications. If there is any question
that even one station will fail to receive a message,
the circuit is unreliable, so if one of the many sta-
tions fails to maintain frequency, the entire system is
discredited.

There is another source of cross channel modula-
tion which is very difficult to eliminate; that due to
spurious radiations and responses. These are most
seriously present in nets consisting of many stations
in close proximity, for otherwise the effects are
usually down 30 to 80 db. below the main carrier, depend-
ing upon the particular equipment. Well designed trans-
mitters will have spurious radiations down at least 60
db. below the carrier, although more would be desirable.

Receiver responses are a bit more complicated.
Spurious responses are due to (1) image-frequency
signals; (2) signals of intermediate frequency; (3)
harmonics of the intermediate frequency generated by

the second detector; and (4) harmonics of the incoming
signal generated in the converter tube. A receiver may
have very good discrimination against adjacent channel
cross talk but may have spurious response due to one of
the above. A good receiver will not respond to spurious
signals giving input voltages of 5-15 micro volts,
depending upon the frequency.

The entire problem of spurious responses and radia-
tions requires close attention by the systems engineer
no less than by the equipment engineer. And there are
not only the spurious responses inherent in the equip-
ment itself, but there are also external spurious
signals, or "stay" noise, developed by nonlinear or
rectifying connections in the vicinity of the receiving
equipment, such as in conduit joints, cables, light
wires, etc. which develop all manners of harmonic and
beat frequencies. This is particularly evident in ship-
board installations where so much communications equip-
ment is concentrated into such a small space. The com-
munications systems designer cannot blithely select the
few frequencies he will need and then ignore the multi-
tude of parasitic radiations which he has conjured up.

Once the engineer has selected the operating band
for the particular communication system he is to build,

it is necessary that he decide upon the method of modulation he is to employ. From the systems viewpoint, the exact method of performing the modulation is not as important as determining the advantages and disadvantages, transmission-wise, of each of the modulation processes in terms of transmission circuit constants. In Table I are appended some of the salient data on the transmission characteristics of each of the modulator and modulation systems listed below. The basic building blocks of radio transmission engineering may be set forth to show their relation, the one to the other.

Sense	Carrier	Modulators	Modulation
Sound	Radio	Hand key	Amplitude
Sight	Wire	Automatic Morse	Frequency
	(Light)	Facsimile	Phase
	(Infra-red)	Telephone	Pulse
	(Supersonics)	Television	a. position
		Teleprinter	b. width
			c. amplitude
			d. numbers

The criteria of excellence should be how faithfully does each system transmit information? how fast? how reliably? how much training is required?, and how much will the equipment cost, in size and weight, as well as money? The ideal communication system should approach mental telepathy for economy of equipment, speed, and independence of physical barriers, though mental telepathy leaves much to be desired as to reliability.

2. Switch Engineering

Switch engineering is the second major province of systems engineering. As a branch of the electrical or electronic sciences, it has had little wide spread attention and has remained an esoteric art, rather than an exact science, until very recently.

Switching involves an almost infinite number of permutations and combinations of the simple operation of opening or closing a circuit by means of a switch. It is the boast of the switch engineer that any complex series of operations can be performed automatically by electric relay circuits faster and more accurately than by humans. And the operations need not be confined to the mere opening and closing of switches, but the processes of hunting for and selecting the correct switch to be operated, ordinarily the domain of human operation, can be performed automatically with less alli-bility than the human. In fact, given enough wire, relays, time, paper, and pencil, the switch engineer can design a circuit to perform any preset desired sequence of operations.

Therein lies the difficulty. The machine cannot think, and each operation it is to perform must be thought out by the human designer beforehand and built into the machine. Any operation not provided by the

designer cannot be performed by the machine, and the machine cannot react to unforeseen circumstances.

The first problem of the designer is to determine exactly what his machine is to do, not in general terms, but in precise step-by-step analysis of the operations to be performed and the contingencies to be met. Then, and not until then, the designer can sit down and calculate the relay circuits required to perform the steps.

The first part of such a problem is not too difficult for it involves functional considerations of operating factors familiar to every engineer. The difficult part of the task is the implementation of these considerations with actual equipment design. The switch engineer has, in the past, been a unique personage of great ingenuity and inventiveness, attaining his aims by exhaustive detailed examination of the problem and endless trial and error experimentation coupled with empirical rules derived from past experiences or inherited from former masters of the art. Like an art, it has remained more a craft than a science, until recently, when a systematic analysis of the art of switching has produced, by the methods of statistical mathematics, a set of rules which clearly define the capabilities of any particular switch circuit. It is safe

to say that any desired sequence of operations can now
be confidently provided by the switch engineer, which
again throws the problem back to the systems engineer
to decide what is wanted in the way of automatic switch
facilities.

Since the machine cannot think, but can only provide
a transfer of skill from the experienced designer to the
inexperienced operator, it is manifestly impossible to
require the machine to perform every possible operation
required by unforseeable circumstances. The machine can
only do that for which it was designed. This places a
very strict limitation on the flexibility of a system
that is built entirely dependent upon the limitations of
the machine. But a naval communication system must be
flexible above all. There must be provision for human
direction and supervision. The human, it has been
pointed out, has just about reached the full limits of
his capability to provide direction to a complex com-
comunications circuit. This is because he is required
to perform many operations of discrimination and
selection of a routine nature leaving little time for
attention to the unique problems of communications. The
machine can be a very valuable adjunct to the human in
the realm of the iterative operations of everyday
routine, leaving the human free to give his full atten-
tion to the pressing operational matters.

One of the major uses of switch circuits is that of selection; that is to pick out and connect one of a multiple of possible connections. This may be done in two ways; first, the selector may connect to a circuit on the basis of a set of determinate orders from a director mechanism, or secondly, it may connect in accordance with the requirement that the circuit to be connected must fulfill certain specific conditions. This second operation might be called hunting or searching, for it is forward looking, as opposed to selection, which is backward looking. The two ideas are similar but to different ends. Selection may be used to energize a particular circuit from a multiple, whereas search circuits will find the particular circuit of a multiple that is energized.

Switch circuits may perform a multitude of functions such as holding, locking, releasing, transferring, and interlocking which are useful in many ways. It is often desired that a certain circuit configuration be maintained indefinitely until a certain signal is received to break the connections. These are hold or lock circuits, depending upon how the operation is performed. The disconnecting signal then originates a release operation which breaks up the hold or lock circuit. The interlock circuits may determine the exact

sequence in which a complicated switch or transfer operation will be performed and will not allow false or unwanted signals to operate the sequence, nor allow essential steps to be omitted.

To proceed further is really fruitless for the number of possible functions which switch circuits may perform are infinite. It is not the intention of this paper to describe the art of switch engineering, but to mention the possibilities of the employment of switch engineering in naval communication circuits. The above mentioned operations are those of most interest in this discussion.

The most fundamental requirement before designing an integrated communication system, is the determination of an overall plan of connection and interconnection, that is, an overall trunking plan. This will determine which stations will be directly connected, and which will be tandem connected. Then it must be determined how these connections will be made, either automatically in response to calling signals, or manually. The combination of the trunking and switching plans form a General Switching Plan by which all design considerations are governed. The switching aspect is paramount in radio nets for nearly all nets are directly trunked

by the very nature of radio itself and the major question is then, how will the connections be made.

It has been mentioned that automatic terminal equipment lacks many of the advantages of the manual terminal in terms of flexibility and complexity of equipment. On the other hand, automatic equipment can perform its allotted duties faster and more accurately than the human can do them manually. It would seem, therefore, that a judicious combination of automatic and manual would have most of the advantages of both.

To illustrate this point, consider a system having ten separate communication channels all mutually available to all stations. It is desired that no circuit may be broken or preempted by other calls when a call is already in progress. A searching mechanism at the calling station is put into operation when the call is put up which tests all channels and connects to the first free channel it finds. The mechanism will refuse to connect into a circuit in which a call is already in progress. After selecting the channel, the sending operator may then send a series of calling signals which operate selection mechanisms in all the other stations. When the prescribed set of signals are received by the called station, its selection mechanism will operate to

complete the connection while all other selection mechanisms will refuse to connect. The incoming call would then be put up on a manual board in the called station only and the call handled from there to the particular internal substation desired. The automatic portion of the network has done the necessary job of selecting and guarding the communication channel yet the manual operation provides the necessary flexibility and human agency to handle the calls in an intelligent manner.

The requirements of a General Switching Plan are that all elements of the communication net be designed integrally to perform in a certain standard, predetermined manner. As long as each element of the net conforms to these standards, they may be connected in any manner prescribed by the General Switching Plan without fear of providing inferior circuits. The crudest illustration of this would be that it would not do for some stations to employ frequency modulation on their carriers while others employ amplitude modulation. This example is so blatant as to be ridiculous but there are other considerations more subtle that can cause as much trouble but are not so obvious. For instance, a General Switch Plan would have to specify the modulation levels of the transmitters and the conversion loss of the receivers, for all stations must, within certain limits,

provide the same signal level into the communication
channel. To fail in this specification would mean that
some stations would always be received better than
others, or that some stations would receive all stations
poorly, due to improper adjustment of the "line" levels.
Such irregularities in the circuit coefficients would
spell the difference between uniformly good communica-
tions and erratic, unreliable communications. This
difference may hinge upon very small details. When a
net is completely manual in operation, the human element
may correct for many of the small errors that threaten
to destroy communications, and each connection may be
made on its individual circumstance. But when a termi-
nal is operated automatically, or even partially so,
the seemingly unimportant details of the circuit must be
rigidly controlled if the system is to operate satis-
factorily. To accomplish this aim, the General Switch
Plan for the system must be very complete and detailed.

3. Component Design

This paper is not directly concerned with the
aspects of component design except as it affects the
operability and reliability of the system as a whole.
Needless to say, inferior equipment will render inferior
service. But in a large communication net consisting
of many diverse but interrelated components, the

reliability of the system is not even as good as the worst component reliability. A good analogy may be made of the problem of equipment life as determined by vacuum tube life. If a piece of equipment has but one vacuum tube and it will last one thousand hours (assuming all other factors constant) the equipment will operate for one thousand hours without breakdown. But if the equipment has one thousand vacuum tubes, each good for one thousand hours, the equipment is due to break down once every hour. The analogy is apparent. As the size and complexity of an integrated system increases, the reliability of the component parts must be increased proportionately if the overall reliability is to be maintained.

Similar considerations are true for maintenance of system quality, as was discussed under the problem of tandem trunking. The capacity of each component link of the system must be greater in terms of band width, "line" loss, and distortion than that of the overall system.

4. Test and Maintenance

Maintenance plays a very large part in all phases of engineering, for machinery cannot repair itself. For complete reliability, trouble must be corrected, not

after it occurs, but before it occurs. Incipient troubles cannot normally be detected by ordinary operation of the system, but must be ferreted out by comprehensive detailed test of the system components, item by item.

Since the General Switch Plan determines the overall operation, it will also determine the operating condition of each of the components. With this as a starting point, it is then possible to develop test procedures to determine that each of the component elements is performing according to specifications. Further, if the system is thoroughly integrated, whole sections may be given routine periodic tests which will quickly determine satisfactory condition of the section. These tests could be given frequently and then, when trouble develops, the entire section can be tested unit by unit to isolate the trouble.

Human nature being what it is, there is no use having a test procedure that is awkward and inconvenient to employ, for then it will not be employed. The test equipment should be designed and built into the system as an integral part of the system and facilities provided to make test procedure as easy and convenient as possible. The test equipment should be installed at one

position convenient to the operating personnel and test outlets provided at that position to all the crucial test points in the system. Thus a brief routine operation at the test position will determine the operating condition of the system and adjustment can immediately be made to correct unsatisfactory conditions. Too, when trouble develops, it can be quickly determined and isolated by use of the test board.

V   SYSTEM DESIGN

1.   General Requirements

This section is intended to provide an example of the methods of system design as contrasted to the approach of technical design. It is the credo of the modern schools of architecture and allied branches of engineering, that form must follow function. In the past history of communication engineering this rule has been practiced in reverse, for the technical designers are little informed as to the particular requirements of naval communications and have provided equipment with excellent technical design but which lack the special features which make them especially adaptable to the naval organization.

The first step of system design is to state the use to which the communication system is to be put.

In intership communications, the problem of hand-
ling long administrative messages is a difficult one.
They are usually too long to be sent via the tactical
circuits and too complex to be intrusted to voice trans-
mission. Visual means of communication are limited in
range and in time. It is necessary that some new method
of rapidly disseminating administrative information be
devised that will not conflict with the existing tacti-
cal circuits, which will have a large traffic handling
capacity, and will reproduce the messages at the receiv-
ing terminals in positive form.

In the absence of definite statistical information
as to traffic experience, the following data will be
assumed.

1. Types of service - - - - - - - - - - Teletype
   (In order of expected use)   Facsimile
                                         Voice

2. Average length of message - - - - 150 groups

3. Maximum number of messages per
   station served per hour - - - - - 3

4. Service area - - - - - - - - - - - - 25 mile
                                        diameter

5. Relay extensions - - - - - - - - - - 75 miles (two
                                        tandem con-
                                        nections)

6. Circuit quality (Carrier/Noise) -- 20 db

7. Minimum line level - - - - - - - - - 47 dbRN

8. Maximum number of stations - - - - 25

Specifications. Channels are to be provided in sufficient numbers so that, on the statistical average, there will always be a channel available for use. All channels will be available to all stations in the system but will be used on a mutually exclusive basis; that is, privacy is to be provided and the channels are to be invulnerable to inadvertent preemption by other stations when in use by one station. (Privacy requires a selective calling system and automatic lockout of unwanted stations.)

Teletype is to be the primary method of communication with alternative provisions for facsimile and voice. These facilities are to be provided at a number of substations within each station. The internal distribution system is to be kept separate from the main intership system through use of a manual board connecting from subsystem into the external system. The internal system will thus be available for intraship communications when not connected through the manual board.

2. System Design

The number of channels required for this system can be determined by the equation

$$N_c = \frac{(\text{stations})(\text{of message})(\text{Messages/station/hour})}{60}$$

$$N_c = \frac{(25)(3)(3)}{60} = 3 \text{ and } 3/4 \text{ (or 4)}$$

With four channels, the system will handle all the traffic among twenty-five stations with the probability that there will always be one channel free. This is based, of course, upon the predicated traffic experience outlined above, and if it develops that the average length of message is longer than three minutes, or that during the busiest hours there are more messages

originated than assumed above, the system will have to
be expanded to provide additional channels.

For administrative traffic it is seldom necessary
that the channels be full duplex, for administrative
messages usually develop ideas or disseminate plans and
information in considerable detail and do not involve
the rapid interchange of thought and commands required
in tactical circuits. The channels can thus be "one-
way" or broadcast channels, with one station using the
channel exclusively for transmitting, and all others
remaining in a passive receiving condition on that
channel. The system will then have four frequencies,
one for each channel, and each station will have facil-
ities for sending or receiving on all four channels
simultaneously.

For several reasons, it may be desirable that no
one station be allowed to transmit on two channels at
once. One reason is technical in nature. With two
transmitters operating in close proximity, the possi-
bility of crosstalk and intermodulation is increased
with interference developing on other channels. It is,
from a systematic viewpoint, undesirable that one station
should be able to "capture" more than one channel for
this would decrease the number of channels theoretically

available to other stations. As a matter of good
practice, each station should be limited to the employ-
ment of one channel at a time. This precludes the neces-
sity of having four transmitters, and one transmitter
per station will suffice, providing it is readily tun-
able to any of the four channel frequencies.

The system will take advantage of the direct trunk-
ing feature of radio to cover the service area, but
beyond the service area, resort must be made to tandem
trunking, or relay. This can be done in several ways,
but only one will be described here as being the most
satisfactory.

It is not desirable that any of the channel fre-
quencies used in the service area be used for relay
work, for this would reduce the number of available
channels for general service. Relay traffic should be
considered as separate from general traffic for it is
not chargeable to the message count within the service
area when taking data for traffic experience. Thus the
figure of three messages per station per busiest hour is
exclusive of relay traffic, for this traffic does not
exist as part of the general area traffic, but is really
switch-through traffic.

Referring back to Figure 11, it is seen that the

same two frequencies are used in alternate links of the relay. Starting at Station l., frequency f_1 may be one of the general service frequencies and is picked up at the first relay station. The intelligence is extracted and used to modulate a special relay frequency f_2. This relay frequency does not then interfere with any of the other general area channels but occupies much the same position in the General Switch Plan as a toll circuit occupies in a telephone General Toll Plan. It is a special through circuit for the exclusive use of long distance traffic. This relay link is terminated at the second relay station which delivers the traffic on another one of the general service channels. By the use of one additional channel, the system has been extended through two relay points. With two relay channels, the system could be extended indefinitely (until limited by signal degeneration), with a reverse channel provided; or outgoing relay traffic can be sent on two channels from the same area, and relay circuits may pass through several general service areas without preempting channels reserved for local traffic.

3. Range of System

The service area has been defined as a circle of 25 miles diameter. This represents a constructive figure for the necessary area of communications for any in-

dependent command at sea. The actual service area is
really not definable in geometric terms but is dependent
upon the relative positions of the various stations to
the center of gravity of the system. But if each station
can provide coverage of 25 miles radius, the coverage
area is then but 25 miles in <u>diameter</u>, for stations on
the periphery of a 25 miles <u>radius</u> from the center of
gravity will be then fifty miles apart and out of radio
range. With use of VHF-UHF equipment, the radio path
cannot be reliably extended much beyond 25 miles and thus
represents the technical limitation to the range of the
system.

The range of a radio link is dependent upon two
factors; the amount of power in the transmitter, and the
sensitivity of the receiver. But the sensitivity of
receivers has reached the ultimate in that the random
noise level sets the lower limit to the input sensitiv-
ity. In the VHF-UHF region, Figure 12 represents the
threshold level of noise below which a receiver cannot
go to detect weak signals. Below 300 mcs. the man-made
noise predominates, but above 300 mcs. all external
noise sources have disappeared below the internal noise
sources of the receiver itself. At about 300 mcs. there
is a minimum of noise in the radio spectrum.

Using the noise distribution Figure 12 and the well

Figure 12. Noise vs Frequency
(graph)

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established empirical formula

$$E = \frac{14 - \sqrt{\dfrac{W}{d}}}{} \quad \frac{\sin(2\,\Pi\,h_t h_r)}{(\quad ld \quad)} \text{ volts/meter}$$

where E is the field strength at the receiving antenna,
    W is radiated power in watts
    h_t is the height of the transmitting antenna in
      meters
    h_r is the height of the receiving antenna in
      meters
    l is the wavelength in meters
and   d is the distance between transmitter and receiver
      in meters.

(It is to be noted that this formula is valid only within the radio path horizon.) The carrier to noise ratio at the receiving station can be calculated. In Figure 13 this has been done for a radio path length of 25 statute miles (22.4 nautical miles) and antennae heights of 70 feet. For a given configuration such as this, the carrier to noise ratio rises at a rate of about 10 db. per octave. This is because of the decrease of effective antenna area as a noise receiving device (noise remaining substantially constant in field strength) whereas the carrier field strength increases with frequency to exactly counteract the decrease in effective antenna area. The curvature at the upper end is due to the sharp rise in noise level with frequency above 300 mcs. The dotted curve represents ratios more nearly obtainable with actual receivers for above 300 mcs. the receiver noise figure falls off at about the rate of 5

Figure 13. C/N Ratio vs Frequency
(graph)

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db. per octave or more. In plotting this curve the
worst condition has been assumed as regards to noise
level, receiver noise figure, receiver band width, etc.
A receiver band width of 10 kc. has been here assumed
though only 6 or 7 kc. will be required for the proposed
types of service. Likewise the noise level assumed was
that for urban districts which have above median noise
levels. The result is that a system built on these con-
servative figures will operate better than required most
of the time and will operate satisfactorily under even the
most difficult conditions. This creates a reserve of
"quality" against trouble from faulty equipment and pro-
vides a margin for relay operations.

The selection of as high a frequency as technical
design is able to provide has several advantages.

    (1) Reduced transmitter power requirements.
    (2) Small physical antennae permitting use of
        arrays.
    (3) Ample Band width available.
    (4) Low noise.
    (5) Fewer anomolous propagation effects.

From Figure 13 it can be seen that an optimum operating
frequency would be at about 400-500 mcs., at which fre-
quency a 35 watt transmitter would provide the specified
20 db. carrier to noise ratio. Because of the present
frequency allocations of this band to aviation aids,
radiosonde, and similar services as well as to military
communications, it may be necessary to use a somewhat

lower frequency, say at 300 mcs. but only a slight dif-
ference in C/N ratio would result.

4. Modulation

Frequency modulation has one quality as a communi-
cation link not to be found in amplitude modulation.
Much has been argued about the noise reducing capabil-
ities of frequency modulation but the real core of the
matter has been somewhat underemphasized.

The most difficult problem in radio communications
is that of maintaining line levels constant regardless
of weather, time, or varying geographical positions.
With amplitude forms of modulation, the signal to noise
ratio of the receiver output is variable with distance
as the carrier amplitude decreases. Of the three attri-
butes of a radio wave, amplitude is the most susceptible
to distortion whereas frequency is the least susceptible
to variation in the process of transmission. Since
frequency, unlike amplitude, is invariant with distance,
then the signal level in a frequency modulated carrier
is independent of the radio path. This feature is very
important in mobile communications where the radio path
is continually changing. The fact that the signal level
in a frequency modulated carrier channel will remain
constant makes it possible to assign the circuit a

definite coefficient and to engineer the system exactly
as though it were a wire line.

The chief disadvantage of frequency modulated
systems is its susceptibility to interference, intentional
or otherwise. The same capture effect, which makes fre-
quency modulation so impervious to interference in fixed
services such as broadcast, works to its disadvantage
when used in mobile services where it is apt to be in
closer contact with unwanted carriers. If the wanted
signal is as little as 6 db. stronger, the receiver will
discriminate very heavily in favor of the wanted signal
and the unwanted signal will not cause interference.
But if the ratio is reversed, the unwanted signal will
capture the receiver and block the circuit. This is
serious in shipboard installations, for the spurious
radiation of transmitters on other channels may easily
be 6 db. stronger than the incoming signal and thereby
block the circuit. With amplitude modulation, the in-
terfering signal must literally "drown out" the wanted
signal by sheer power and the amount of interference in
the output is directly proportional to ratio of inter-
ference to carrier at the antenna. This is not so for
frequency modulation, for there is an improvement factor
operating in favor of the stronger signal. Unfortunate-
ly, the receiver is unable to distinguish which signal

is the wanted signal, but merely reacts in favor of the stronger.

The many factors concerned, when considered in their entirety, tend to favor frequency modulation. The fact that, within the service area, the circuit coefficient remains constant regardless of radio path promises more uniform and stable communications with frequency modulation. But also there are several other factors not to be ignored. With a given set of tubes, a frequency modulated transmitter may be operated to the full rating of the tube, an increase in power of about ten percent. The modulation equipment is negligible, for modulation may be performed at low levels and Class C amplifiers used thereafter.

There is no reason why the relay links cannot, on occasion, employ medium or high frequency amplitude modulated carriers for long distance links without in any way affecting the operation of the local service.

Having selected frequency modulation, it is time to consider the requirements of the types of modulators specified for service on this system.

The highest frequency required to be sent is 3000 cps. Both voice and facsimile require this band width

though the lower limit for voice is 250 cps. and that
for facsimile is about 2100 cps. For teletype, it is
possible to use frequency shift methods of modulation,
for frequency shift keying is closely allied to fre-
quency modulation. Without going into the technical
details, it is possible to place any of the three types
of modulators upon the carrier within the same band
width and with the same frequency modulation deviation.
Any of the three may be placed upon the circuit alter-
natively without any alteration of the equipment or the
mode of operation of the circuit. Since this is a
broadcast system, there must be a prearranged operating
procedure, for there is no opportunity to talk back and
forth on the circuit. It is expected that teletype will
be the main service channel with facsimile and voice
being used for special services. All stations will
ordinarily receive with teletypes on the line and will
shift to the other forms only when directed.

5. Switching

This entire system is dependent upon the successful
design of the terminal selecting and switching equipment.
Many of the functions required of the system can only be
done by automatic switching and general employment of
the traffic handling techniques developed in telephony
systems. For flexibility and speed, it is necessary to

use both automatic and manual switching, with the automatic switching doing the vast majority of the work.

There are two requirements for this system; automatic lockout of unwanted stations, and privacy. The first can be provided by the use of automatic channel selection at the sending stations so that the equipment will never connect to a busy channel. The second requirement can be met by selective dialling connections at the receiving stations. Selective dialling can be made most flexible; and calls may be dialled to connect one station, particular groups, or the entire net may be dialled, calling in all stations for a general conference. Any dialling combination desired can be provided such that every ship, every command, and every command echelon could have separate call designations. In this way, the problem of channeling calls to the desired addressees is automatically solved. A destroyer squadron commander could connect separately to any one ship within his command, connect separately to any one of his division commanders, or connect to all of his division commanders collectively, or to any division as a whole, or to his entire squadron collectively, merely by dialling the correct combination.

Once a connection is made through the automatic terminal, it is put up on the manual board of the called

station. The four receiving channels are brought out at
this board, along with the apperances for the relay link
transmitters and receivers. Also appearing on this
board are all the substations of the internal system.
On incoming calls, the connection must be made through
the switchboard (though it may be patch connected for
any desired length of time) to the internal system which
will have its own design pattern to fit the needs of the
particular ship or station. The only requirements on
the internal system of the station is that it meet the
external system with a match in impedance, line level,
and frequency response characteristic. Beyond that, the
systems are independent. On outgoing calls, the order
is given to the switchboard operator who then connects
the internal system to the external system and dials.
Upon release of the dialling key, his work is done.

The exact configuration or lay out of the switch-
ing terminal is not important in this discussion as
long as the salient features of its operation are clear.
The main points in its operation may be set forth in
summary as follows =

1. The Channel Selector tests the output of each
    receiver (with CODAN) and will stop only on an
    idle channel. The stepping action of the selec-
    tor also selects the proper channel for the
    transmitter, brings it to that channel, and puts
    it on the air. The lost time between channel
    selection and transmitter tune up must be small.

If the selector finds no idle channel, it will step along to a busy connection, and give a BUSY indication to the operator. The above sequence of operations is activated by the insertion of the input connection in the board.

2. <u>The operator dials</u> the desired station. The fact that there is now a carrier on the air prevents interference by any other station inadvertently attempting to use the channel. This provides lock out of other stations. An emergency provision could be made that the operator, by closing an emergency switch, could cause the channel selector to connect to the first channel in its course, and the transmitter then be energized. The operator could then break-in and direct the channels be cleared for emergency traffic. This detail would be quite difficult, and should be unnecessary.

3. <u>The incoming signal</u> operates the CODAN which connects to the selective ringer. The dial pulses operate the ringer and connect the receiver output through to the manual board. The operator answers the indicator light by connecting a teletype reperforator and awaits further connecting instructions. He may be instructed to connect through to some particular substation, or he may take the entire message on his reperforator and then retransmit on the internal system for delivery and routing.

4. <u>The relay links</u> are brought out entirely independent of the rest of the terminal and is handled on a full manual basis. Supervisory signals may be by voice, or by selective tones, from the sending operator.

6. <u>Future Planning</u>

This system has been built on the unit of four channels which is also the normal number of ships in a tactical division. On independent maneuvers, each ship in a division could thus preempt one channel and provide full duplex operation. There is no reason, however,

why switching provisions for, say, ten channels should
not be built into the system so that it is merely neces-
sary to add another transmitter and four receivers in
order to double the system capacity. Large ships and
commands might even have eight channels while the smaller
units have but four. The channels would be split at the
manual board so that the large units could use half the
facilities for communications among themselves, reserv-
ing the other channels for the smaller units, which,
though greater in number, do not originate so much traf-
fic.

VI CONCLUSIONS

The successful systems designer must have three
attributes.

1. Technical knowledge of the possibilities
   and limitations of electronics to perform
   required tasks in the projected systems
   plan.

2. Operational knowledge of the requirements
   of the particular service to be served
   coupled with a complete understanding of
   the philosophy and structure of communica-
   tions.

3. Imagination.

The principles of systems design are very broad and
defy strict classification. This is due in part to the
many diverse purposes of communications systems and in
part to the fact that any particular problem may be
successfully solved in several different ways. It is

the attribute of imagination on the part of the engineer
that enables him to devise and select the best solution
for incorporation into the particular system under con-
sideration.   It might almost be said that the only really
general principle of systems design is attention to
minute details in synthesizing the solution, and strict
adherence to the highest, most exacting standards of
engineering design consistent with the economic consid-
erations of the problem.

TABLE I

This table is not intended to be definitive in all the technical aspects of modulations and modulators, but is meant to provide salient information on the particular aspects affecting system design.

Voice telephony

Spectrum: 250-3000 cps. The human voice is a complex of the frequencies from 100 to 10,000 cps. but adequate quality is provided using only the band 250-3000 cps. The power of the voice resides in the low frequencies whereas the intelligence is modulated in the higher frequencies. The normal power level of the voice is about 100 db. below 1 watt/ square centimeter, with a variation of plus or minus 10 db. between the strong and weak talkers. Converted into electrical energy by standard microphones, these levels correspond to normal line levels of about -4 dbm. with a spread of plus or minus 3 db. between strong and weak talkers. Peaks of the order of 8 to 10 db. above the norm may be caused by broad vowel sounds which have high power content. A voice to noise ratio of 6 db. is the minimum ratio for marginal intelligibility and 13 db. should be the minimum allowable for engineering purposes.

Manual
telegraphy

Spectrum: 0-50 cps. Telegraphy is a direct current signalling system wherein the current is interrupted in conformity to an intelligence code. The transient harmonics generated by the keying are a function of the keying speed. If tone modulation is used, the spectrum is that of the tone, plus and minus the keying spectrum. The average telegrapher can achieve a speed of as much as 25 or 30 net words per minute for short periods, though 15 - 20 net words per minute is the usual average for long periods. (Net words per minute is based on words of text per minute of circuit time. The time consumed

in headings, addresses, and operating instructions is charged as circuit time.) However, manual telegraphy has the advantage of being able to operate under marginal conditions when all other systems are blanked out by noise.

Automatic
  telegraphy   Spectrum: 0-300 cps. High speed Morse code sent from prepared tapes and recorded automatically on inked tapes. Provides a positive record of traffic, eliminating the psychological effects on the receiving operator. Operates at high speed (300-400 net words per minute). Experienced personnel still required for operation of equipment and transcription of messages from receiving tape.

Teleprinter   Spectrum: 0-23 cps. Keyboard printing operations are converted into direct current telegraphic code signals for transmission on wire or radio links. Keyboard operations can also be made to prepare tape for automatic sending, or operate other machines to print message in page or tape form. Has advantage over other forms of telegraphy in that transcription from code is done automatically by the machine and no experienced personnel are required to transcribe text. Inexperienced personnel can achieve speeds of 20-25 net words per minute in keyboard sending while tape sending is at a standard speed of about 50 net words per minute. (60 words per minute sending speed.)

Facsimile
  Black & White   Spectrum: 0-500 cps. (dependent upon definition). Will transmit printed page copy or line drawings. Scanning of copy determines whether black or white signal is to be sent and systems operates in an on-off manner. Speeds of as high as 300 words per minute may be obtained when sending from the best copy (clean black print) and photographic methods of recording are used.

Ordinary speed from typewritten copy
and direct recording is nearer 50 net
words per minute. One disadvantage of
facsimile is that the quality of re-
ceived copy cannot be regenerated at
relay points except by preparing new
originals. On the other hand, fac-
simile records the actual received
signal permitting reconstruction of
text destroyed by noise. This differs
from teleprinter which makes an inter-
pretive decision as to the incoming
signal and then prints a character.
The teleprinter cannot discriminate
except against impossible code combina-
tions. If noise alters the apparent
code, the teleprinter will print what
it thinks it receives, not that which
is actually received. Because of this
factor, facsimile can operate under
more adverse noise conditions than
teleprinter.

Facsimile
  Half tone

Spectrum: 9-2000 cps. Transmission
requirements are much more stringent
for half tone printing than for any
other type of communication circuit.
Line levels must be kept within 1 db.
during transmission and delay distor-
tion must be less than 3 milliseconds.
Variations in line level will change
the picture contrast and change the
level of black and white. Variation in
delay will cause the formation of
"ghosts" and shadows.

Television

Spectrum: 0-4,000,000 cps. (Depend-
ent upon definition). Television is
essentially high speed facsimile using
transient recording on a cathode ray
tube, enabling it to transmit moving
scenes. The value of television as a
pure communication system is proble-
matical because, for just communica-
tion work, it does nothing that other
systems don't do better. It may have
limited usefulness in intelligence
communications and for broadcasting
fast moving operations (such as a CIC
plot in combat operations.) The

extremely high quality circuits re-
quired for television do not give
returns commensurate with energy and
equipment required.

Modulation

Amplitude modulation.

The amplitude of the emitted
carrier is varied in accordance
with the modulator signal. Max-
imum modulation amplitude is
equal to the carrier amplitude
which makes the circuit net loss
variable with distance. The
sideband energy is supplied by
the modulator system and amounts
to 25% of the carrier power at
100% modulation. For given tube
size, the carrier power, when un-
modulated, must not be more than
80% of power capabilities of
tubes. Noise has a predominately
amplitude characteristic so that
amplitude modulation systems are
inherently unable to discriminate
against noise.

Frequency modulation.

The frequency of the carrier is
shifted in accordance with the
modulated intelligence. The am-
plitude of the carrier is not
altered except as incident to the
frequency modulation process.
Full modulation is an arbitrary
design definition dependent upon
system requirements, and may be
sent at any level. Overmodulation
has no meaning except as a design
definition. Modulation level is
independent of carrier amplitude
and thus independent of radio
path. Modulator need supply no
power to the side bands for side
band power is derived at the ex-
pense of the carrier power. The
output tubes in an FM transmitter
thus may be operated always at
full output power rating. By
limiter action in the receiver, FM
discriminates against noise.

Phase modulation. There is no significant difference between FM and phase modulation in operational aspects. The main differences are of technical significance only.

Pulse modulation. Pulse modulation is essentially a form of amplitude modulation since the carrier is first pulse modulated and then the pulses are themselves modulated in accordance with the modulator intelligence. Since the receiving equipment is sensitive only to the particular modulation on the pulse, and not to the modulation of the carrier itself, it is insensitive to the various types of distortion which affect the carrier. Pulse modulation can be achieved in four ways.

1. amplitude-amplitude of pulse varied as in ordinary carrier amplitude modulation.
2. time - position of pulse in time is varied about the average or mean position. Is like phase modulation.
3. width - the duration of the pulse is varied with modulation.
4. Numbers - the number of pulses which occur in a unit interval of time is varied with modulation.

The chief advantages of pulse modulation are (1) the high peak power level possible in pulse technique, (2) possibilities of clipping to eliminate noise, (3) multiplexing by time sharing of carrier since no channel needs the carrier longer than for its pulse to be registered. The band width of the system varies inversely with the pulse length and for a 1 microsecond pulse is about 2 megacycles. At the present state of the art, directive arrays are necessary to concentrate the power towards the

receiver. For this reason pulse
modulation systems are not suited
to naval communications.

BIBLIOGRAPHY

The material for this discussion was drawn from so many varied sources, including informal conversations, that it is impractical to provide credit notations for every item incorporated herein. The following bibliography includes all published sources employed in the writing of this paper.

Automatic SOS Alarms
    Electronics, April 1937

Aspects of Radio in Telephone Systems
    Bell Telephone Laboratories

Absolute Sensitivity of Radio Receivers
    RCA Review, Vol.6 January 1942

Communication Engineering, W.L.Everitt
    McGraw-Hill, New York

Considerations Entering into the Choice of
  Frequencies for Air Communications
    Paper by Martin Katzin, Naval Research Laboratory

Crossbar Dial Telephone Switching Systems
  F.J.Scudder, J.N.Reynolds
    Electrical Engineering, Vol.58, 1939

Crossbar Switch, The, J.N.Reynolds
    Bell Laboratories Record, Vol.15, 1936-37

Decade of Progress in Use of Electronic Tubes,
  Part I - Communications, S.B.Ingram
    Bell Telephone System Monograph B-1268

Development of Relay and Switch Circuits, A.E.Joel,Jr
    Mass. Inst. of Tech., Master's Thesis

Director in Automatic Telephony, The, C.W.Brown
    Inst. of POEE, Paper 116-1927

Electrical Communication Systems Engineering
    War Department TM 11-486, 25 April 1945

Future of Transoceanic Telephony, The, O.E.Buckley
    Bell Telephone System Monograph B-1346

Fundamentals of Teletypewriters Used in the Bell
  System, E.F.Watson
    Bell System Tech. Jour., Vol.17, October 1938

Great Lakes Ship Radio System
   Electronics, October 1944

History of Automatic Telephony, The, A.E.Joel, jr
   MIT, Graduate Seminar, 1940

Lockout Circuits, F.A.Korn
   Bell Lab. Record, Vol. 18, No. 1, September 1939

Modern Systems of Multi-channel, A.S.Angwin, R.A.Mack
   Jour. of Inst. of Electrical Engineers, Vol.81, 1937

Multi-carrier Communication System
   Wireless World, June 1946

Multi-channel Army Communication Set
   Electronic Industries, June 1945

Multi-channel Pulse Modulation
   Wireless World, February 1946

Narrow Band Telephone Transmission, J.A.Csepely
   Electronics, March 1940

Noise Figures of Radio Receivers
   Proceedings of the Institute of Radio Engineers
   July 1944

Operation of a Ship-to-Shore R-T System
   Proc. of IRE, March 1932

Operational Functions of Naval Command
   Naval War College, 1945

Planning a VHF Communication System - Mass. State Police
   J.A.Doremus, Electronics, September 1943

Radio and Electronics in the Navy
   Electronics, April 1943

Radio in Naval Tactics, W.B.Ammon
   Scientific American, November 1935

Radio Extension Links to the Telephone System
   R.A.Heising
   Bell System Tech. Jour., Vol.19, October 1940

Radio Facsimile
   RCA Ind. Tech. Press

Radio Facsimile by Subcarrier Frequency Modulation
    R.E.Mathes, J.N.Whitaker
    RCA Review, October 1939

Radio Telegraphy and Radio Telephony, E.E.Rickard
    Jour. of IEE, Vol. 84, 1939

Recent Developments in Diversity Receiving Equipment
 J.B.Moore, RCA Review, July 1937

Reference Data for Radio Engineers
    Federal Telephone and Radio Corp.

Radio Engineers Handbook, F.E.Terman
    McGraw-Hill, New York

Selective Calling Systems, J.K.Kulansky
    Electronics, June 1946

Ship-to-Shore Radiotelephone, R.H.Riddle
    Electronics, September 1937

Ship and Shore Terminal Equipment, A.S.Angwin
    Electrical Communications, July 1930

Some Mechanical Aspects of Telephone Apparatus, J.D.Tebo
 H.G.Mehlhouse, Bell Tel. System Monograph B-1354

Telecommunications of the Future, W.G. Radley
    Engineering, November 21, 1941

Telephone Circuits Used as an Adjunct to Radio Broadcasting
 H.S.Foland, A.F.Rose, Elect. Comm. January 1925

Telephone Theory and Practice - Automatic Switching
 and Auxiliary Equipment, K.B.Miller
    McGraw-Hill, New York

Telephony and Telegraphy, W.G.Radley
    Jour. of IEE, Vol.84,1939

Theory of Automatic Telephone Systems, A.E.Joel, jr
    MIT, Bachelor's Thesis, 1940

VHF Communication Equipment   .
    Wireless World, June 1946

Vogad for Radiotelephone Circuits, A
    Proc. of IRE, Vol. 27, No. 4