Concise Papers

Telemedicine: New Application of Communications Technology

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Abstract—Telemedicine may be defined as the practice of medicine at long distance by means of telecommunications, in particular, closed-circuit television and telemetry. Two-way television enables physicians to establish a nominal doctor–patient relationship with patients at a remote location, while providing the means for visual examination of patients. Biomedical telemetry transmits patients' vital signs, detected by standard medical bioelectric sensors and physiological function transducers.

In a telemedicine simulation experiment, a test group of physicians deemed black-and-white television adequate for most diagnostic purposes, but expressed a preference for color. The group evidenced little interest in picture resolution greater than that provided by the standard U.S. 525-line system. The Plumbicon camera was said to provide better pictures for medical purposes than the vidicon. In either color or black-and-white television, lighting is a critical factor in the proper rendition of flesh tones as well as in providing the necessary illusion of depth for the observation of detail. Commercial television lighting practices are directly applicable. The inclusion of certain colored items in the televised scene aid in the interpretation of color television pictures.

Designing the biomedical portion of a telemedicine system requires knowledge of the various electrical characteristics of the vital signs to be transmitted. These cover a wide range of frequencies and amplitudes. Most bioelectric potentials are so small that special care must be taken to avoid artifacts produced by electrical interference.

INTRODUCTION

By means of a telemedicine system being installed in Puerto Rico, physicians at a major hospital will be able to examine, diagnose, and prescribe treatment for cases entering a small health center over 30 mi away. Two-way closed-circuit television will support the doctor–patient relationship and permit physicians to visually examine patients, X-rays, and laboratory specimens. Electrocardiograms, blood pressure, pulse rate, respiration rate, and other vital signs will be transmitted to the physicians by telemetry. A special audio circuit will transmit heart sounds picked up by an electronic stethoscope. The physicians will be able to relay prescriptions to the health center via telewriter.

The prototype of this system was the Telediagnosis system installed in 1968 between Boston's Logan Airport and the Massachusetts General Hospital. That system has proven the validity of the telemedicine concept. The Puerto Rican telemedicine system will serve as a further demonstration of the utility of the concept by fulfilling a critical medical care need. At the same time, it will function as a test bed for determination of system design criteria.

Both systems are forerunners in a new application of current telecommunications technology. All of the television, telemetry, and medical instrumentation techniques and hardware required for telemedicine systems have already been developed in other applications. This paper tells how they can be brought together in a system specifically designed to extend the services of medical specialists beyond their physical confines.

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ELEMENTS OF A TELEMEDICINE SYSTEM

Basically, a telemedicine system consists of patient examination facilities at one location, diagnostic display and recording instrumentation at another, and a telecommunications transmission system linking the two. Closed-circuit television and associated audio provide audio–visual contact between parties at both ends of the system. The patient examination facilities provide local indications of the measured parameters as well as the electrical signals for transmission to the consultation terminal. Fig. 1 shows the television system configuration for the patient examination facility. The examination room has two television cameras for patient observation. One is equipped for remote control by the consulting physician at the other end of the circuit. The other is a viewfinder-type camera for operation by a doctor, nurse, or other paramedical personnel in the examination room. A third camera, equipped with a special lens adaptor, is used in conjunction with a microscope for viewing laboratory slides.

A large television monitor in the examination room enables the patient to see the consulting physician. A small monitor and video switch panel mounted on the local doctor's control console permits examination room personnel to select a picture of the consulting physician or the picture being picked up by any of the examination room cameras. A screen splitter in the console provides for a simultaneous presentation of pictures from the two patient examination cameras.

The television equipment at the consultation terminal consists of a remote-controlled camera that the physician can train on himself by means of the controls mounted on the consultant's control console, and large and small picture monitors. The large picture monitor is wall mounted for viewing by the physician and other consultants or medical students. The small monitor is contained in the control console.

The physician's video equipment includes a video pointer that electronically inserts a pointer image for loopback to the examination room to point out areas of particular interest or to instruct paramedical personnel in the placement of the electronic stethoscope or other probes.

The control rooms at both ends of the system are fully equipped for monitoring and testing the video signals. The camera control units for all cameras are located in the control rooms, to enable the engineers to make the necessary electrical adjustments without direct access to the cameras. For reasons of privacy, a special control circuit permits the physician to disable the engineers' picture monitors. The waveform monitors are not affected.

The audio facilities associated with the television system consist of microphones with directional pickup patterns appropriate for the layout of the examination room, microphone amplifiers, loudspeakers, and the associated audio amplifiers. A private voice circuit between the consultant's console and a telephone outside the examination room is a useful adjunct to the voice communications in that certain conversations between medical personnel should be restricted from the patient. Physicians consider it part of the art of medicine to impart information to the patient in such a way as to enhance treatment.

A special audio circuit operates in conjunction with the electronic stethoscope for the transmission of heart and respiratory sounds. This circuit is restricted to an upper frequency of 400 Hz, in keeping with the requirements of phonocardiography. Higher frequency sounds constitute noise in clinical practice.

The medical diagnostic equipment includes a three-channel electrocardiograph, an automated sphygmomanometer (blood pressure cuff), a pulse rate monitor, a respiration rate monitor, and possibly an electromyograph and four-channel electroencephalograph. As shown in Fig. 2, all of the equipment provides a local readout as well as a signal for transmission to the consultant's console. The associated analog data transmitters and receivers are located in the respective control rooms.

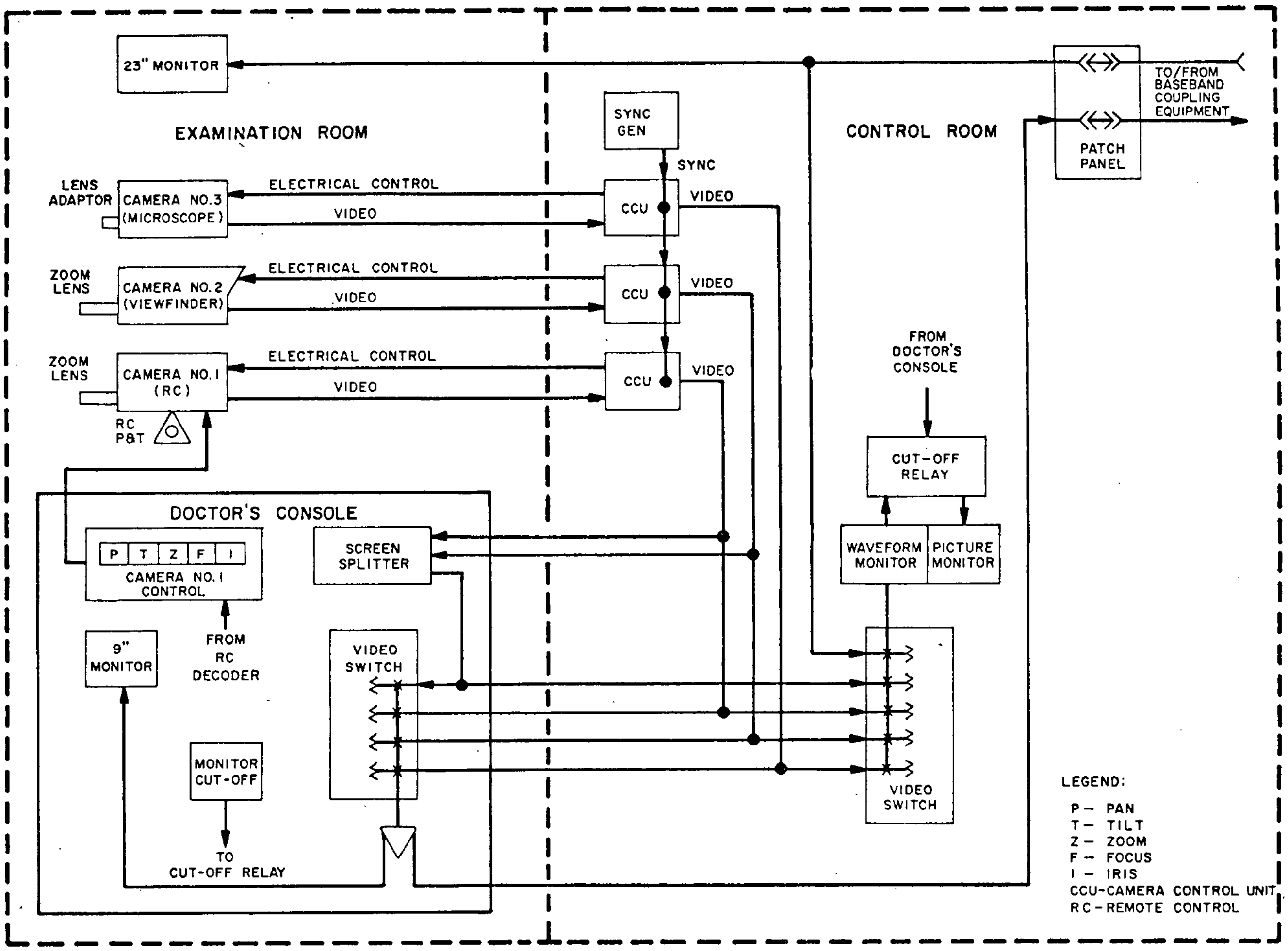

Fig. 1. Examination facility video system.

TELEVISION SYSTEM

Telemedicine Experiment

To determine the television system design parameters for the Puerto Rican telemedicine project, the Institute of Social Technology, Puerto Rico, conducted an experiment in which a number of physicians were asked to provide their reactions to a simulated telemedicine setup incorporating variations of monochrome (black-and-white) video [1]. The physicians reported that black-and-white television provided adequate information for accurate diagnosis, although there was a general consensus that color would be preferable. In at least one instance, a dermatology case involving a severe skin inflammation, the specialists attempting diagnosis had to request verbal communication of color values. In another case, leprosy was correctly diagnosed in a very dark-skinned man when closeups of his skin and eyes were shown by means of a zoom lens with a closeup lens attached.

With regard to image tubes, dermatologists reported that cameras using a Plumbicon (lead-oxide) tube displayed skin texture better than those using the vidicon. All observers reported a preference for the Plumbicon pictures and there was only one instance in which they reported better resolution of detail from the vidicon. Another reported factor in favor of the Plumbicon was its lower image lag with respect to the vidicon.

The experiment included both 525-line and 945-line scans. The physicians expressed little interest in the higher resolution provided by the 945-line system. In view of the bandwidth economy of the standard 525-line system and the apparent lack of physician interest in a higher resolution picture, the Puerto Rican telemedicine project will utilize the standard 525-line scan for the basic system. To support further experimentation along this line, however, the system will include a 10-MHz channel for high resolution television. This channel will support approximately 800 lines of horizontal resolution. Cameras and monitors will be capable of at least 700-line center resolution. The vertical resolution will remain 350 lines because of the 525-line scan. A screen splitter will enable the pictures from both cameras to be viewed side by side for comparison.

Lighting for Television

In telemedicine, whether it utilizes black-and-white or color television, proper rendition of flesh tones is of major importance. Since colors, or the gray shade counterparts as we perceive them, are influenced by the ambient lighting, consistency of lighting is a primary concern. Instead of trying to define and reproduce "true" color, it is more useful to establish a reasonable set of lighting conditions that can be maintained and repeated. With the lighting held constant, the only variable will be the different skin tones which enter into the diagnostic process.

In engineering a lighting setup, we can take advantage of the considerable experience built up in commercial television, where one of the major concerns has always been the proper rendering of flesh tones.

Light Levels

The factors involved in producing light of various intensities are the level of the light incident upon a scene and the reflectance of the scene. The resulting light level determines the camera lens opening required, which in conjunction with the focal length of the lens determines the depth of field. Except for artistic effect, the smaller lens opening produces the best results in that it provides the greater depth of field. (An added advantage is that it reduces the possibility of accidentally burning the image tube.) In commercial black-and-white television, $f/11$ is commonly used in conjunction with base

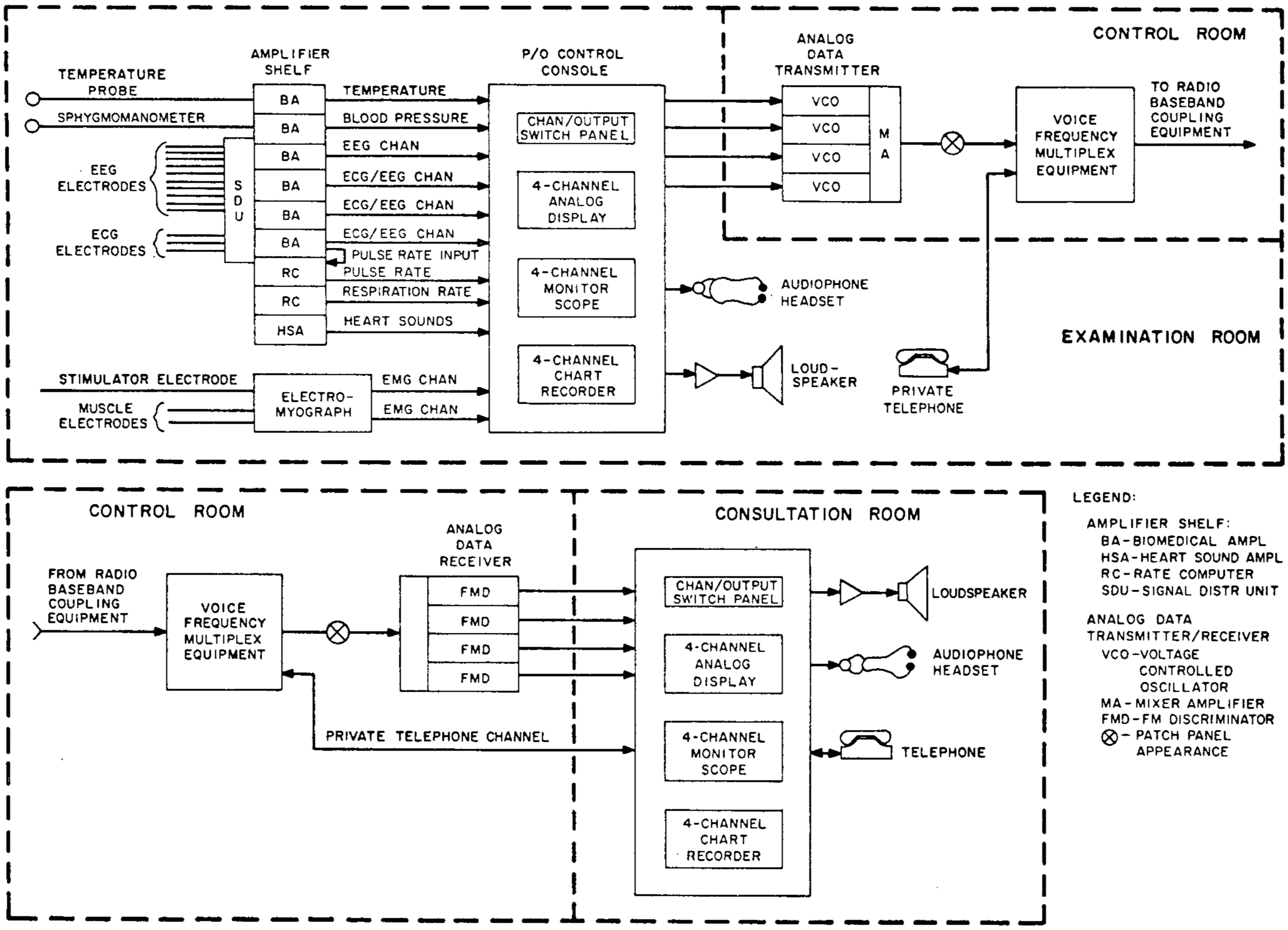

Fig. 2. Telemedicine system biomedical instrumentation.

lighting at a practical nominal value of 100 fc. The usual values for color are $f/8$ and 250 fc [2].

Lighting Types

Base lighting is diffused lighting that lights all elements of a scene as nearly as possible with the same intensity. The result is a flat textureless picture that would have little value as a tool for medical diagnosis. Therefore, key light should be added to give the effect of a single predominant light source, with the attendant shadowing and texturing. The effect of a predominant source is achieved when the key light intensity is one to two times that of the base light [3]. To avoid overly brightening the scene, the base light coming from the direction of the key light should be reduced by a corresponding amount. Thus, the key light becomes the camera operating parameter while the base light serves as fill light, reducing the depth of shadows.

Back lighting, which provides pictorial separation between subject and background, may be used to enhance perception, depending upon the position of the patient and his location relative to the background. It will be useful if the patient is seated or standing and the shot desired is of the patient's body or a significantly large part of it. It would serve no purpose if the patient were lying on an examination table and the shot were from directly above, or if the shot were a closeup of some portion of the anatomy. Back lighting should be held at one to one-and-a-half times that of the base light for monochrome and from one-half to one for color. Excessively high angles of back lighting must be avoided because of the excessive shadowing it produces.

Lamp Capabilities

Both incandescent lamps and quartz-vapor lamps are used in commercial television lighting. Each has different characteristics and many lighting engineers employ combination of the two types to advantage. For telemedicine applications, however, the characteristics of the quartz-vapor lamp are such that it should be used exclusively. Of primary importance, the quartz-vapor lamps put out the rated color temperature for their entire useful life, whereas the incandescent lamps shift toward red (lower color temperatures) as they age. Furthermore, the power and air conditioning requirements for quartz-vapor lamps are less than those of the incandescent lamps.

A 2000-W incandescent lamp in operation as a floodlight provides a level of 648 lx over a spread of about 2 m at a distance of 6 m. The standard quartz-vapor luminaire, at 2000 W with a 12-in lens, spreads 648 lx over 5 m at a distance of 6 m. In other words, the quartz-vapor lamp provides almost the same coverage as three incandescent lamps.

Special Lighting Requirements for Color

Quartz-vapor lamps are available at color temperatures of either 3000 K or 3200 K. Commercial television usually applies 3200 K, although color television cameras can be balanced to studio lights of either color temperature. For consistency of color rendition, once balanced, the same color temperature should be maintained. This is achieved in the first place by using the quartz-vapor lamps and secondly, by maintaining the set (room and surroundings) colors constant.

The maximum contrast range in color television should be held to 5 to 1, which corresponds to a range on the EIA gray scale of steps 2 through 6. Background material and lighting should be low in saturation, medium in luminance, and preferably of matte surface. "Holes" should be filled with either Fresnel-lens spotlights or scoop floodlights, as the situation requires. Since specular reflections produce "hot spots" that impair the picture, mirrors and chrome, or other polished reflecting surfaces, must be kept out of the scene.

To provide a reference base for color interpretation, the setting should include small areas of white, black, and the colors of the three primary color channels. This will avoid the necessity for color interpretation by an observer on the scene.

BIOMEDICAL TELEMETRY

As important as television is in providing the capability for visual examination of a patient, it is possible to conceive of a telemedicine system without television, a system based solely on the telemetering of biomedical data. Conventional medical diagnostic instrumentation provides biomedical data in electrical form suitable for transmission. Special biomedical amplifiers process the minute electrical potentials generated by the "firing" of body cells to produce the electrocardiograms (ECG's), electroencephalograms (EEG's), and electromyograms (EMG's) commonly used in clinical practice. Various types of transducers convert the physiological parameters of temperature, blood pressure, pulse rate, heart sounds, blood flow, and respiration volume into electrical signals. Telemetry equipment is available for the transmission of the wide frequency and dynamic ranges of these biomedical signals.

The biomedical telemetry setup diagrammed in Fig. 2 is sufficiently extensive to support diagnosis by specialists in the various medical fields. It could be made even more elaborate with considerable justification. In view of the role of telemedicine in enabling specialists to consult on cases at long distance, a system of lesser capability, however, would not be cost effective.

The characteristics of the biomedical amplifiers, the signal processing equipment, the display and recording devices, and the transmission equipment depend upon the frequencies and the dynamic ranges of the biomedical signals of clinical interest. The frequencies range from dc to 2000 Hz, while the bioelectric potential amplitudes detected by surface electrodes range from a few microvolts to a few millivolts.

The physiological measurements provided by transducers in the system shown in Fig. 2 are temperature and blood pressure. The transducer most commonly used in temperature probes is a thermistor. It provides a logarithmic output, but is required to measure only a relatively small temperature range (32 to 43°C). The rate of change of body temperature results in a frequency response requirement of dc to 0.1 Hz. The sphygmomanometer, which can take the form of an automated blood pressure cuff of the type used in automated multiphasic health test applications, requires an amplitude range to accommodate readings from 0 to 400 mmHg and a frequency response of 0.5 to 100 Hz.

The bioelectric signals cover a much wider range of frequencies and potentials. The basic component of heart activity is on the order of 1 Hz, but certain significant characteristics of an ECG waveform vary at rates as low as 0.05 Hz. These waveforms also exhibit relatively abrupt voltage changes corresponding to frequencies above 100 Hz. In phonocardiography the essential information is contained in a band from 25 to 1200 Hz. In research applications, frequencies of up to 2500 Hz are of interest. Specially designed heart sound amplifiers for phonocardiography have adjustable or selectable bandpass filters to eliminate various portions of the lower frequency end. The resultant emphasis on the higher frequencies is useful in the analysis of heart murmurs.

For auscultation, on the other hand, it is important to screen out frequencies above 400 Hz, since they constitute "noise" to the examining physician. Moreover, in electronic stethoscopy it has been found useful to employ special earphone headsets called audiophones. They resemble acoustic stethoscopes in sound reproduction characteristics as well as in appearance. Loudspeakers have little value in this application because physicians require the improved low-frequency response provided by the increased acoustical coupling of the earphones.

EEG's have certain identifiable waveforms within the range of 0.2 to 100 Hz:

1) 0.2 to 3.5 Hz: delta wave
2) 4 to 7 Hz: theta wave
3) 8 to 13 Hz: alpha wave
4) 14 to 100 Hz: beta wave.

EEG voltage amplitudes range from a minimum of about 10 μV to a maximum of 300 μV (peak to peak). Typical waveforms average 50 μV peak to peak.

EMG's, which record muscular activity, have frequency components ranging up to 5 kHz, although those of clinical interest lie between 50 to 200 Hz. Typical voltage amplitudes range from 100 to 500 μV, with a maximum on the order of 10 mV.

CONCLUSIONS

The telemedicine concept, which makes possible the provision of specialized medical care at locations not served by medical specialists, requires only the application of well-known and proved techniques and equipment from the fields of closed-circuit television, television broadcasting, medical electronics instrumentation, telemetry, and wide-band radio relaying. While absolutes with regard to television mode or operating parameters have not yet been defined, criteria are available for planning and designing telemedicine systems that will provide physicians with the necessary tools for diagnosis and treatment. Of particular importance in telemedicine is the engineering of lighting systems to provide consistent rendition of flesh tones with the necessary resolution, clarity, and depth. Telemetry requirements for the transmission of analog data can be keyed specifically to the known useful bandwidths and dynamic ranges of the various bioelectric and physiological signals and parameters to be measured in diagnosis.

REFERENCES

[1] J. W. Eckerling and H. E. Moore, "Medical communications technology: A demonstration simulation experiment," pt. II, Inst. Social Technol., San Juan, Puerto Rico, Rep., June 4, 1971.

[2] H. E. Ennes, *Television Broadcasting Equipment, Systems and Operating Fundamentals.* Howard W. Sams & Co., 1971, pp. 408–413.

[3] ——, *Television Broadcasting Camera Chains.* Indianapolis, Ind.: Howard W. Sams & Co., 1971, p. 17.

[4] G. H. Sullivan, C. Hoefner, and V. C. Bolie, "Electronic systems for biological telemetry," in *Bio-Telemetry*, L. E. Slater, Ed., in *Proceedings of the Interdisciplinary Conference on the Use of Telemetry in Animal Behavior and Physiology in Relation to Ecological Problems.* New York: Pergamon Press, 1963, pp. 84–85.

[5] J. R. Landoll, "Characteristics of ECG machines," in *Clinical Electrocardiography and Computers*, C. A. Caceres and L. S. Dreifus, Ed. New York: Academic Press, 1970.

Random-Access Digital Communication for Mobile Radio in a Cellular Environment

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***Abstract*—A random-access digital multiplex system is considered in the context of a cellular mobile radio system. Three different ways of implementing this technique in a cellular system are described. With the aid of certain simplifying assumptions, the techniques are compared as to their traffic-carrying capacity.**

I. INTRODUCTION

Consider a situation in which there are a number (N) of statistically identical and independent digital data sources, each generating traffic at random (and with appropriate buffering) to be sent to one common point. If the N sources are geographically separated and all transmit to the central point over a common channel (without intercommunication by auxiliary means) there is generally a loss in performance as compared to the situation in which all N sources are at the same location and are combined to feed a common buffer which is emptied on a first-come, first-served basis by a single transmitter. The easiest way to appreciate this is to imagine (for the N separated sources) the common channel divided into N subchannels by some orthogonal multiplexing technique [e.g., time-division multiplexing (TDM), frequency-division multiplexing (FDM)]. Each low-speed subchannel has (all other things being equal) $(1/N)$th the capacity and a traffic input $(1/N)$th as large as for the common channel with combined sources. As a result,

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