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LARGE
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NETWORK DESIGN FOR STRUCTURAL MONITORING IN HIGH-RISE BUILDINGS

ABSTRACT

In order to improve understanding of behavior, including failures of high-rise structures, bridges, and other large structural systems, field data from large amounts of sensors are necessary. These data may be analyzed and help determine failure modes and set design standards. A network design for integrating information sensor outputs in a high-rise building is presented in this report. A particular application would be to monitor earthquake and wind effects. The design is based on packet switching theory concepts and the packet radio used in this design is found to be ideally suited for collection of earthquake and wind effect data in a high-rise building.

Massive amounts of hard wired sensors pose economic and flexibility problems. The issue addressed in this report is if a wireless digital communication technique is used in a high-rise building to gather data during events such as strong wind or earthquakes, what sort of protocols should be used? Are there existing protocols which may be adapted to this problem?

A network design which is centrally controlled is discussed by visualizing the network topology in two sections - backbone network and floor communication network. The backbone network, consisting primarily of radio repeaters, overcomes the proximity limitations of radio propagation characteristics and is capable of establishing communication between all floors from the basement to the top floor of the building. The floor communication network, which is responsible for controlling the floor sensors, is controlled by the central controller of the network.

Functional requirements for each unit in the network are discussed in detail followed by an analysis of the performance of the network. Performance measures of the network considered are delay in packet transmission and throughput of the network. A theoretical calculation of these quantities is carried out by taking into account the probability of loss of a packet during transmission. Packet transmission delay associated with hop by hop versus end to end acknowledgment is compared and it is shown that for non negligible probability of loss of packets, hop by hop acknowledgment is superior for a high-rise building.

For a specific example of a 50 story building, the maximum delay time for the total system of sensors to respond with the developed network design is calculated to be about 0.15 sec compared to a typical period of vibration of 2.5 sec for such a building.

ACKNOWLEDGMENT

This paper is the result of restructuring P. Arumugam's 1989 Lehigh University Master of Science Thesis in Computer Science and Electrical Engineering entitled "Network Design for Integrating Information Sensors in A High-Rise Building". In this paper, there is increased emphasis in the use of wireless digital communications techniques. Professor R. Denton, Lehigh University, Department of Computer Science and Electrical Engineering was Ms. Arumugam's thesis advisor.

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CHAPTER 1

BACKGROUND

1.1) INTRODUCTION:

In order to understand the sensor requirements and the type and amount of data which are necessary to capture the salient features of a structure during an earthquake event, a number of experts were interviewed and numerous papers were reviewed. With this review, a problem of data handling was considered. Suppose one wished to collect information from an event for a hundred story building with one hundred sensors per story for which accurate data could be gathered with the highest frequency component of interest from ten to one hundred Hertz. This event may last thirty seconds with significant after-shock data requirements. Thus a minimum of thirty million data points would have to be collected.

This scenario and a strong desire for ease of reconfigurration of sensors led to the study of suitable wireless digital protocols to accommodate large numbers of sensors each of which has a small amount of data for each sample. This problem is nearly the reverse of other common digital communication protocol requirements where large amounts of information are to be transported from a limited number of information sources.

This study started with introductory fact finding regarding wind and earthquake effects on structures in order to establish the requirements for a data network. Network topics were reviewed with relative merits of various communication media and topologies. The favored medium and topology was selected and rationalized, then issues leading to throughput and timing requirements were considered.

The network selection was a primary backbone with repeaters on each floor for top to bottom connectivity. Each floor had a concentrator which communicates with the floor repeater. The concentrators communicate with clusters of sensors which may or may not have intelligence of their own. The backbone terminates in a master computer/controller which could be shadowed. The network accommodates two distinct modes of operation, that of triggering data acquisition in the case of a significant event, and that of routine polling for data. The communications scheme was kept very simple primarily to aid realistic implementation. Statistical reasoning was used in the selection of a preferred handshake between nodes in the repeater chain of the backbone.

Concluding remarks encompass the suitability of this network protocol choice as well as some reference to further studies which may lead to an economically viable and flexible system for capturing information on structural responses to events to be used for later analysis.

1.2) REQUIREMENTS OF SENSORS IN HIGH-RISE BUILDINGS:

High-rise buildings have become an important technical advance in the twentieth century. The attraction of high-rise buildings though predominant in major cities, is spreading to the suburban regions and smaller cities. Every technical advance leaves behind its impact not only on the improvement in standard of living but also on the environmental conditions. High-rise buildings are no exception to this rule. Several regulations have been developed to reduce the impact of high-rise buildings on the environment, in the broader sense of the word. However, more emphasis is laid on the safety and serviceability requirements of such structures. [1]

An integrated system of sensing elements and monitors is needed to collect the enormous amount of data required to perform safety analysis. The data are analyzed by appropriate instruments and processors and matched with the preset limits. [2] When a violation of the limits or unusual or emergency conditions occur, measures are taken to alert people of the situation or impending danger. Natural phenomena like wind, earthquake, etc., cause damage to structures both gradually and sometimes drastically depending on the magnitude of the forces exerted by them. Instrumentation is needed to monitor and study the occurrence and effect of these causes to enable safe maintenance of the structures and provide data for future designs. Building response is determined from the data, such as seismic acceleration and wind pressure, obtained during an event. In order to capture data with the least amount of delay, it is necessary to organize the instruments into a computer network. When designing indoor communication for high-rise buildings, there are many factors which play a significant role in the choice of characteristics of the network and these are considered in this paper.

1.3) REQUIREMENTS AND CLASSIFICATION OF SENSORS:

Sensor technology has evolved in a direction which allows combining sensors and electronics. The full potential of microelectronic techniques is being exploited by application of a microprocessor, which allows making use of sensors that could not be used before because of problems such as nonlinearity. Adding a microprocessor provides a way of including polygonal correction or of adding a look up table of numerical factors to compensate for nonlinearity. It is only necessary that the sensor response is consistent. Flexibility of sensor instrumentation is high with microprocessors. The microprocessor might calibrate the signal, compensate for known errors, and be used to program the sensor's interface so that it can be tailored to different applications. [3]

In line with the above discussion, sensors can be divided into two categories:

1. Sensors with self contained electronics
These sensors are ones which are combined with a microprocessor and digital signal processing. Because of the digital output, they are easy to use for computer-based data acquisition and for digital display. Digital output of these sensors also provides insensitivity to interface induced noise.

2. Sensors attached to a signal conditioner, and to a digital processor.
These sensors are the traditional analog sensors. As the analysis of any instrumentation usually requires computer processing, it has become essential to transform their analog output to a digital output.

1.4) INTEGRATION OF SENSORS FOR EARTHQUAKE AND WIND EFFECTS:

There are a large number of sensors that can be used for measurements in a high-rise building and these sensors have to be integrated in ways to allow for monitoring earthquake and wind effects. In order to analyze the data collected during the occurrence of earthquake and wind monitoring, signals from the sensors have to be transmitted to the data collection system. The signals from the sensors have to be conditioned and converted to a suitable format for data transmission. An automated system can be used to collect data from both earthquake and wind effect sensors. The system should be triggered externally using reference/trigger signal.

Earthquake sensors have to be triggered at the time of an earthquake and external seismic triggers should be located in the basement of the building where the building first experiences the ground acceleration of the event. The seismic trigger in the basement can be set to trigger the sensors at all levels of the building once the ground acceleration exceeds a preset value. Differential pressure transducers can similarly be initiated by the automated system whenever strong winds occur. In order to capture all heavy winds and storms, it is necessary to provide a reference pressure system. Generally the wind speed at the top of building is used as a reference wind velocity.

Measurements of building accelerations, strains in columns, or deflections can also provide valuable information about the whole structure and response to the wind effects.[4] It can be seen that integrating the earthquake and wind effect sensors into the same data collection system is possible except that the required reference and triggering mechanism used in initiating the sensors is different in both events. In order to design a network integrating the sensors and enabling communication among them, factors that play a significant role are considered next.

CHAPTER 2

NETWORK CONSIDERATIONS

2.1) CHOICE AND RELATIVE MERITS OF TRANSMISSION MEDIA:

One of the key technical considerations in network design is the choice of a transmission medium. The transmission medium may be a pair of wires, coaxial cable, radio waves, optical fibers, or infrared transmission through the atmosphere. Transmission media differ in relative cost, due to the nature of equipment required for information transmission, installation, and maintenance. Before making a choice it is necessary to review the pro's and con's of the available choices of medium for a specific system application. Following is a brief discussion on the characteristics of several different transmission media.[5]

<u>Twisted pair:</u> Twisted pairs of wire are a form of transmission line, i.e. a means of conveying signals from one point to another. Transmission over twisted pairs can be analog or digital using a variety of signaling approaches. Digital techniques often employ Pulse Code Modulation (PCM). Twisted pairs can be employed for both point-to-point and multipoint applications. When used for multipoint applications, average data rates are restricted, dropping as the distance increases between devices due to propagation delays. Energy loss is an important parameter to be considered when utilizing twisted pair in a high-rise building. As distance between the communicating devices increases, the energy loss also increases. At times, the loss is so high that the receiver will not be able to detect the information. Twisted pair is a poor choice for a high-rise building due to signal strength attenuation and susceptibility to noise and other interference.

<u>Coaxial cable:</u> Coaxial cable is a form of transmission line similar in concept to twisted pair, but with modified construction. The cable has an inner conductor with an outer conductor concentric to and completely surrounding it, which is usually grounded. Between the inner conductor and outside conductor is dielectric and the entire cable is housed by a casing. Coaxial cables are usually classified in two ways according to the modulation techniques employed, baseband or broadband. Baseband transmission implies no frequency translation of digital signals transmitted; transceivers drive data onto the cable using a variety of coding techniques. Broadband coaxial cable transmission often implies frequency or phase modulation techniques, transmitting analog signals along the cable. Immunity to noise for coaxial cable networks is highly dependent upon the application and the implementation. Though broadband coaxial cables could achieve more signal distance than the baseband cables, they suffer from the disadvantage of higher per foot cable cost and installation costs. Also, any addition of equipment or reconfigurability involves significant additional cost. Coaxial cable is not considered to be suitable for high-rise buildings for reasons such as low flexibility for reconfigurration, high associated cost, high susceptibility to noise and other interfering sources.

<u>Fiber optics:</u> Optical fiber transmission is implemented by transmitting a signal encoded beam of light through an optical cable, consisting of a group of discrete optical fibers that each transmit a light signal from one end of the cable to the other. Transmission takes place within the infrared frequency range, 10^{14} to 10^{15} Hz. Optical fibers are unaffected by electromagnetic interference, noise and

crosstalk. Optical fibers exhibit very low signal losses and it is possible to achieve communication links over long distances using fiber optic networks. However, fiber optics is not considered to be the best suitable medium for a high-rise building information sensor network because fiber optics implementation is more expensive than twisted pair and coaxial cable in terms of cost per foot of cable and required equipment such as transmitters, receivers, connectors etc. In addition, expensive optical couplers, taps and multiplexing techniques and devices are required for multidrop applications.

Infrared: In addition to fiber optics, information can be transmitted at infrared light frequencies through free space. Light sources for the infrared transmissions include both LED sources and lasers. The atmosphere imposes severe restrictions on the range and error rates for infrared transmissions due to absorption, scattering, turbulence and refractive index variations. Infrared light transmissions are unaffected by electromagnetic interference and noise. But these transmissions are currently limited to point to point communication only. Also, free space infrared communication devices are expensive. Infrared is not suitable for indoor communication.

Radio: The use of communication systems based on radio transmission has several advantages. The main one is that there is no physical medium, such as a cable, to be installed. Instead, the medium is the atmosphere and a significant reduction in cost results. A further advantage is that the network nodes may be mobile. Local network utilization of radio as a transmission medium revolves around packet radio technology. So far packet radio networks have been constructed primarily for military use where transmitters and receivers are on vehicles and are therefore mobile.

However, packet radio technology for local networks in high-rise buildings appears feasible. Using currently available technology, it is possible to obtain expansion in bandwidth, improvement in signal to noise ratio, and high transmission rates with no associated cabling cost. Radio is suited for both point to point and broadcast connectivity. Packet radio offers a highly efficient way of using multiple access channels, particularly when large numbers of users are to be integrated. Details on packet switching theory can be found later in this chapter.

COMPARISON OF DIFFERENT TRANSMISSION MEDIA:

Potential media for intrabuilding communication are twisted pair, coaxial cable, fiber optics and radio. Among these, radio appears to be the most suitable for integrating information sensors in a high-rise building. The main advantages of packet radio network over networks utilizing other transmission media are that they are not dependent on fixed topologies, are easy to establish, and can operate unattended. [6] In addition, at the time of an earthquake that damages the structure itself, chances of obtaining information from sensors is higher with the network employing radio than the one with the cables. These cables can experience relatively high damage in such cases so that data may not be available. Thus, radio is the choice for a network transmission medium for high-rise buildings.

With radio as the transmission medium, reconfiguring the network is easy i.e., it is possible to add any additional equipment required without affecting the operation of the network and with little additional cost. However, the network still requires a topology to be defined for successful operation. In the following section, different types of topology suitable for radio are discussed.

2.2) CHOICE OF NETWORK TOPOLOGY

For a packet radio network, the network topology can be mainly categorized into

1. Point-to-point connection
2. Multipoint connection

In point-to-point connection, two radios are connected by a single channel and this channel is dedicated to these two radios. In case of a multipoint connection, there will be several radios sharing the same channel. One of these radios will be attached to the central computer which acts as the central controller, also known as the primary station. Other radios attached to the network act as secondary stations. Each secondary radio has its own address and is designed to recognize and respond to that address. [7]

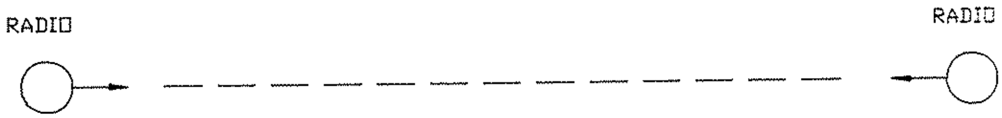

Fig (1) Point-to-point communication

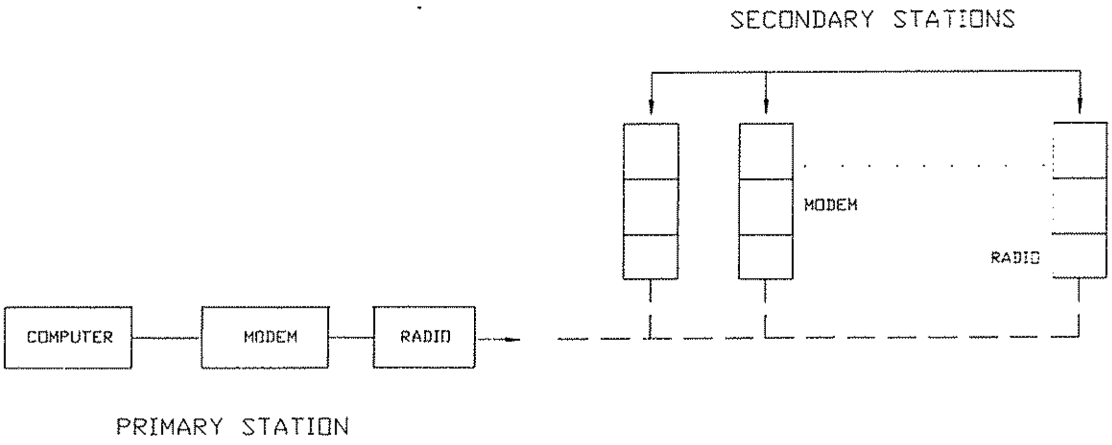

Fig (2) Multipoint communication

Multipoint packet radio network structures are classified broadly into:

1. centralized-star,
2. distributed,
3. multistar centrally controlled,
4. multistar distributed.

Centralized star:

The centralized network also known as a star network is depicted below:

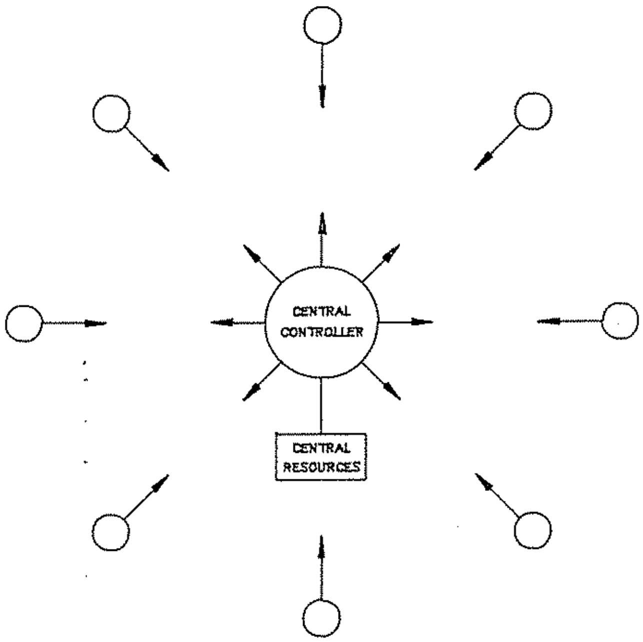

Fig (3) Centralized (Star) network

In a centralized system, two radio channels are required. Individual stations send packets to the central station on one channel, and the central station broadcasts packets on the other. Since radio transmission is omnidirectional, packets transmitted by the central station are heard by all the secondary stations provided these stations are in line of sight propagation with the central station. A star network structure is appropriate for applications that require a centralized data base and a centralized processing facility.

Distributed network:

A distributed network is characterized by a multiple connection between stations. Figure 4 illustrates the distributed network structure.

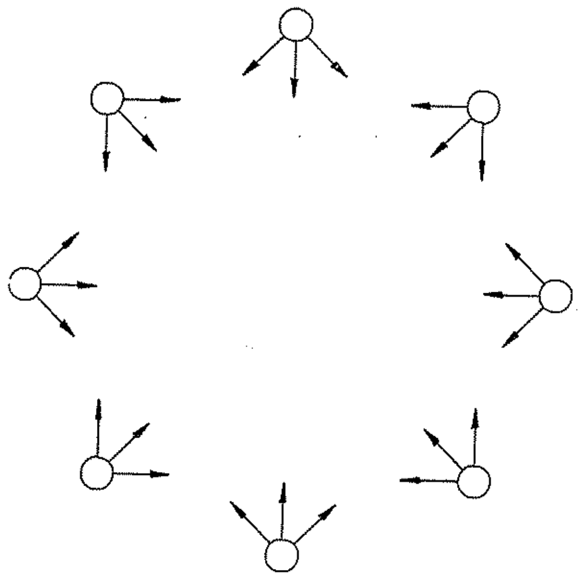

Fig (4) Distributed Network

Distributed architecture is appropriate for situations where all stations are required to communicate with each other. Any large system that requires computer facilities at remote areas to communicate and coordinate on a regular basis is provided by a distributed structure. An important advantage of the distributed network is higher system reliability. Reliability of the network is dependent upon availability of the alternate routes in case of a link or a station failure. Here again, it is assumed that these stations are in line of sight of each other.

Multistar Network:

A multistar network structure with a central controller is one in which the points of a centralized star become centers of additional stars and form a tree like structure.

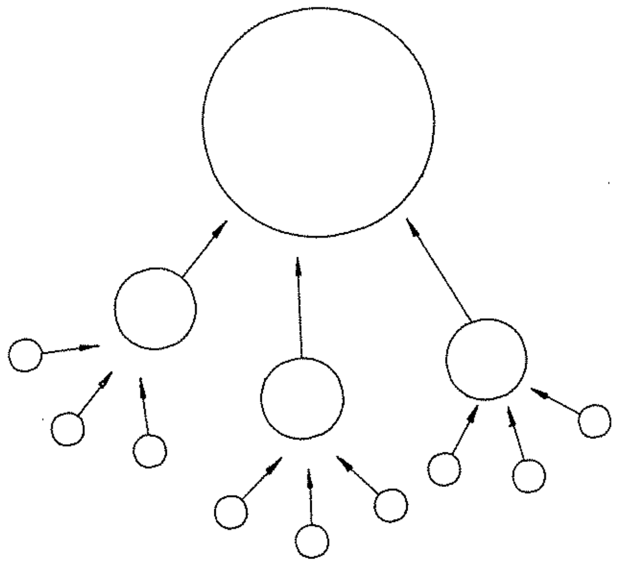

Fig (5) Multistar Network - Centrally controlled

Multistar network with distributed control is shown below:

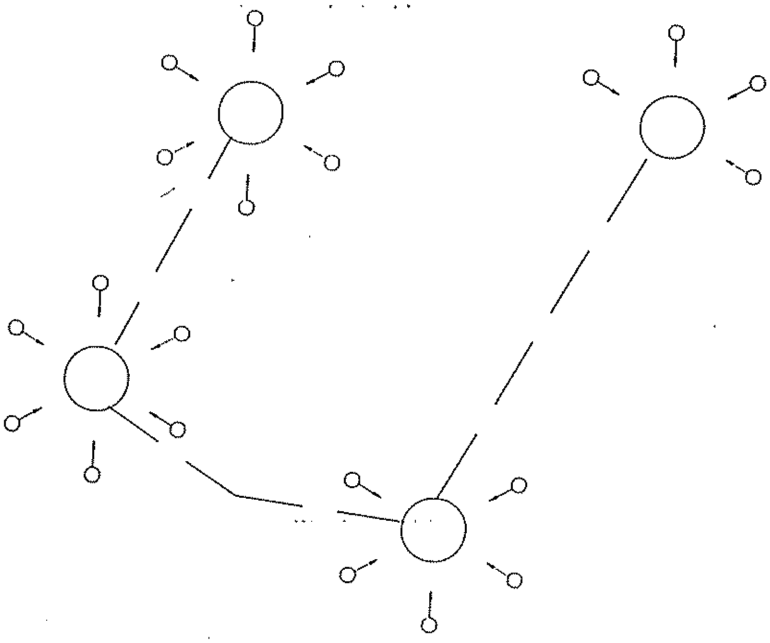

Fig (6) Multistar Distributed Network

ARPANET is an example of a multistar distributed network.

Store and forward repeaters in Centralized and Distributed networks:

A store and forward repeater is used to overcome proximity limitations. A repeater performs the same task as the station in a packet switched network. In a centralized system, the repeater accepts packets from the central station and retransmits them to remote stations.

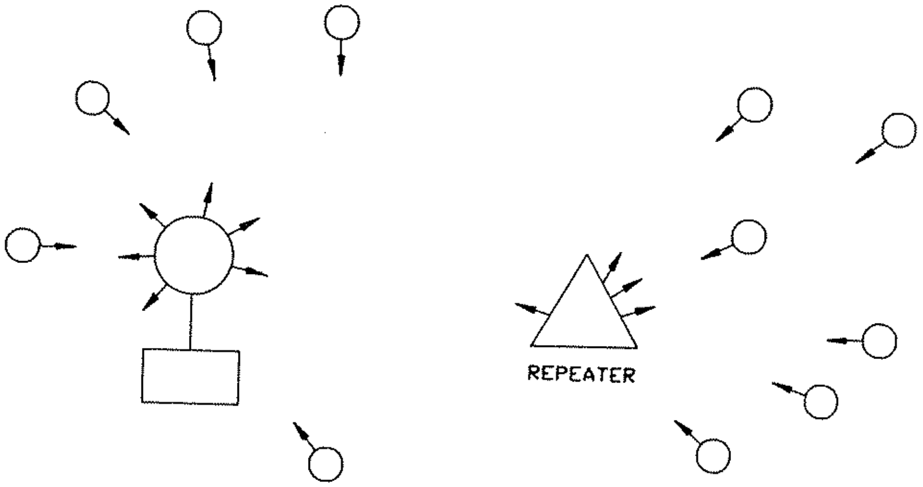

Fig (7) Store and forward repeaters in a centralized network

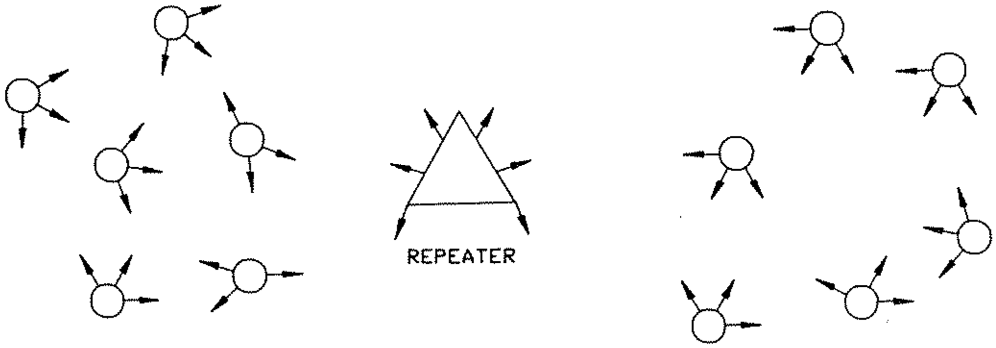

Fig (8) Store and forward repeaters in a distributed network

In a distributed system, the repeater acts as a switch between two sets of stations, accepting packets from one set for retransmission to the other and vice versa.

CHAPTER 3

NETWORK DESIGN

3.1) SELECTED NETWORK TOPOLOGY

Requirements for high-rise building instrumentation to study the effects of earthquake and wind effects include sensors at every floor which are activated by a central controller. The central controller sends a message at the time of an event; i.e., when an earthquake occurs and the external seismic trigger actuates, the central controller is required to trigger the sensors at all levels of the building. At the occurrence of heavy wind, the anemometer kept at the top level of the building monitors the wind level and is sent to the central station. Based on this value, the central controller activates all wind effect sensors at all levels of the building.

Since the building has as many as N floors, it is not possible for the central controller to directly communicate/monitor all sensors mounted at each floor. Grouping the sensors by floor level with a local controller at each floor will enable the central controller to establish communication via the local controller on each floor. Every sensor is attached to a radio and sensors at each floor are in direct communications with their floor concentrator by radio. In this fashion, it is possible to establish communication between the sensors and the floor concentrator.

Floor concentrators however, are controlled by the central controller. Thus these floor concentrators may not be in direct contact with the central controller, it is necessary to provide radio repeaters at every floor. At every floor, there is a single repeater and a single floor concentrator. Radio repeaters provided at every floor overcome the limitation of propagation. Store and forward repeaters of a centralized network, as shown in Fig (7) are suitable. With repeaters acting as the backbone of the network, a radio repeater kept at a particular floor level is capable of communicating to its floor concentrator in addition to the repeaters kept at one floor above and one below. By integrating these floor concentrators with the repeaters at their corresponding floors, the limitation due to the height of the building can be overcome. Taking these points into consideration, the network topology selected is shown in figure (9). Certain assumptions made in this network design are listed below.

Assumptions:

1. There are N floors in the building.
2. Floor concentrators have radio connectivity with their respective floor sensors via radios. In other words, all sensors attached on a floor are in direct radio contact with the concentrator of the floor.
3. A repeater at every floor is in direct radio contact with the concentrator of that floor.
4. The repeater has a buffer of limited size. (4 - 6 packets)
5. Each floor is identical with reference to the floor network topology. This assumption makes it easy to develop the networking management software at the central controller. There are no more than M sensors at every floor.
6. The concentrator at each floor is assumed to have infinite buffer capacity.

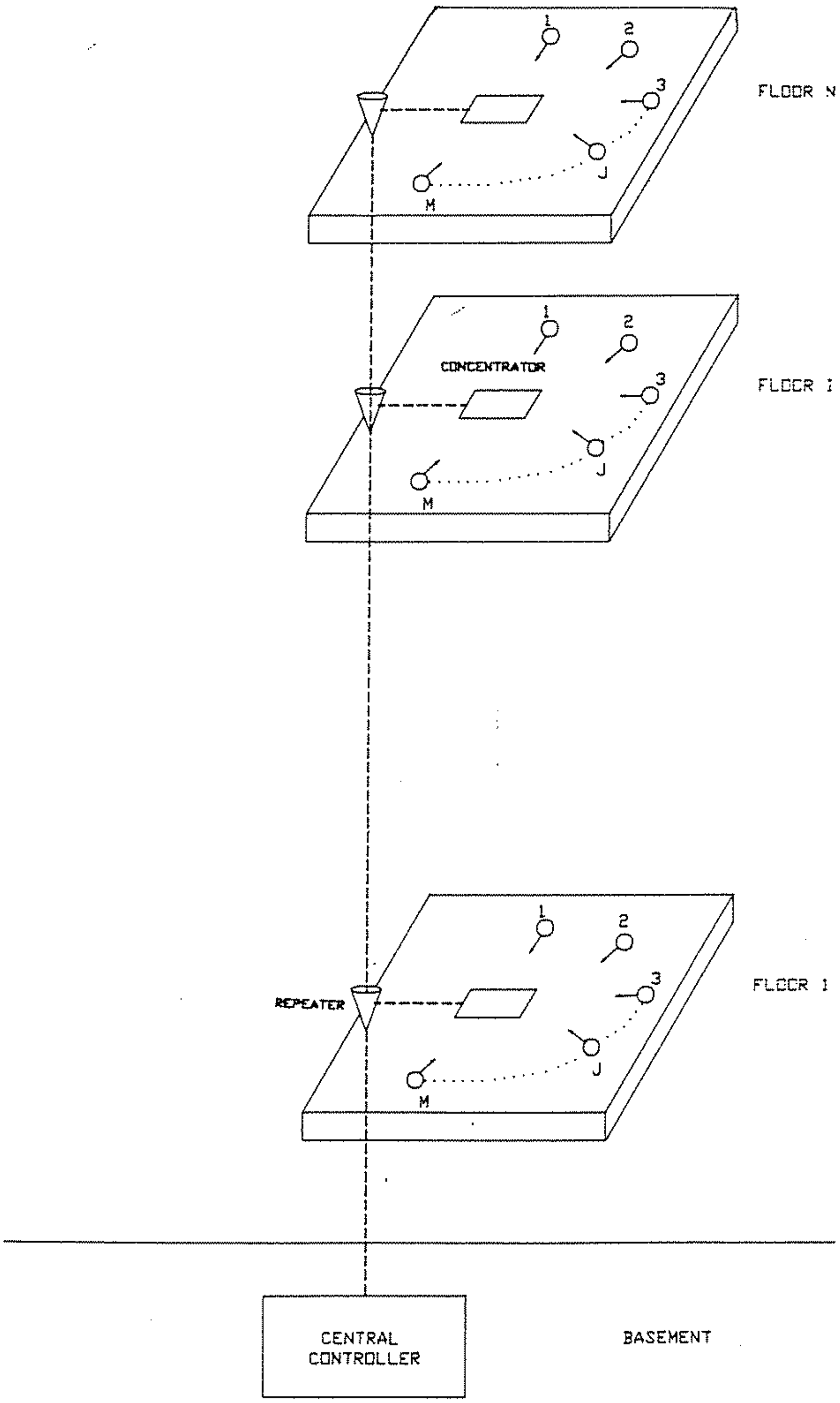

Fig (9) Selected Network Topology

The sections following provide further analysis of the network topology design. Selected network topology can be analyzed by visualizing it in two sections - backbone network and floor communication network.

Backbone network:

The backbone network consists of a central controller acting as the primary station, and the floor concentrators as secondary stations with the floor concentrators logically connected to the central controller using radio repeaters at every floor. These repeaters are necessary to extend the communication range/distance that can be covered by the central controller. They make it possible to establish communications between the central controller which is kept at the basement of the building and floor concentrators of each level. This is depicted in the figure (10).

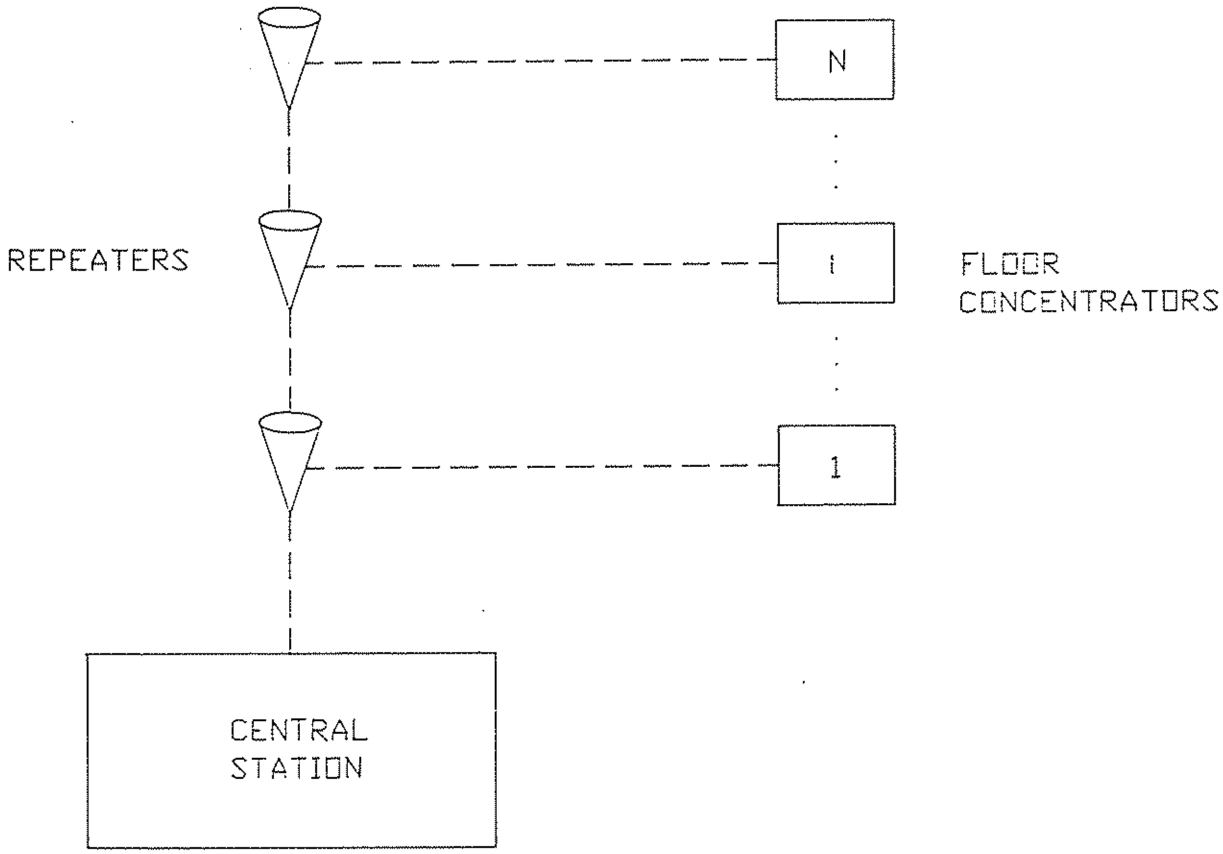

Fig (10) Primary and secondary stations

Floor communication network:

Floor communication is a centralized star network with the floor concentrator attached to a radio acting as the primary station. (or a local controller). Each sensor attached to a radio acts as secondary stations. Every floor has an identical communication network and is shown in figure 11.

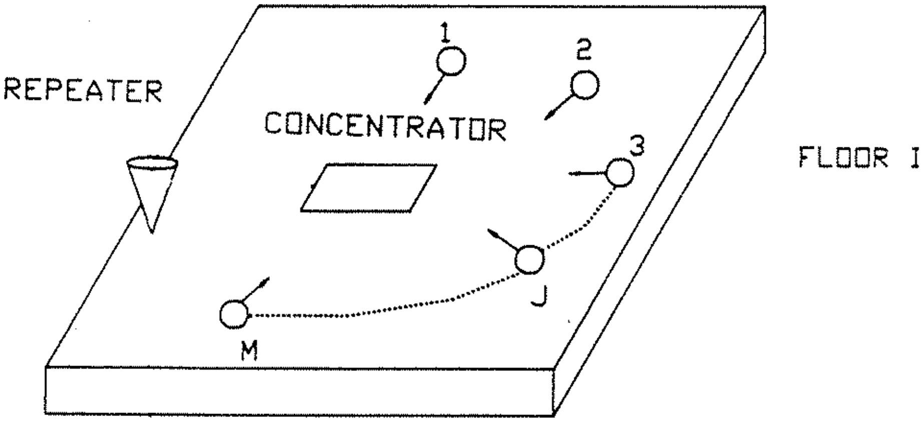

Fig (11) Primary and secondary stations at floor level i

From figures 10 & 11 one can see that the network topology is a mixture of topologies. A star configuration is provided at the backbone level which gets expanded to a tree like structure. Points of the star become centers of additional star structure performing switching functions at the floor level.

3.2) FUNCTIONAL REQUIREMENTS

Packet radio is a technology that extends packet switching concepts. Packet switching technology was pioneered on the wired networks and is referred to as X.25 packet nets which are used by common carriers for both domestic and international data communications. All packet switched systems, whether land line or radio, share a common principle of operation. In the network described here, every unit is attached to a packet radio in order to transmit and receive data. A discussion of the concept of packet switching theory employed by the packet radio is given below and followed by the specific functional requirements for each unit.

3.2.1) PACKET SWITCHING THEORY:

Data assembled into packets:

In a packet-switched network, data are assembled into blocks before transmission. Each block is a form of "electronic envelope" and this envelope is called a packet. Packets are allocated to carry data. Packets are of varying size depending on the amount of data input. If data input to the system is greater than the maximum size of a single packet, two or more packets will be sent containing sequentially numbered portions of the original data. The process of assembling data into packets and then combining the packets at the destination station is usually called PADing - Packet Assembling and Disassembling. PADing takes place transparently, i.e. without the user being aware of it. [8]

Validation of Data:

Once the data have been assembled into a packet, it is offered to the network for broadcast. The packet will be heard by all stations within the range. However, it will be ignored by all stations except the one to which it is addressed. Upon receipt, the receiving station will check the validation bits, which are appended to the data. If the packet is intact, a positive acknowledgment (ACK) is returned to the sender confirming receipt. Should the validation process indicate a transmission error, no ACK will be transmitted. The sending station expects to receive an ACK for every packet it sends. Failure to receive one initiates a retransmission of the packet. The validation process is essential to the operation of a packet system. There are a variety of methods used ranging from simple parity sums to sophisticated Cyclic Redundancy Check. Single bit parity checking is easy to implement but suffers from an inability to detect an even number of bit inversions. The cyclic redundancy check (CRC) is more complicated but offers corresponding improvements in performance. The CRC - 16 is chosen by X.25 common carriers as well as by most of the packet radio systems.

Sharing a channel:

Since stations organized into a packet network will only respond to data addressed to them, one channel can be shared by all stations. Since a packet system allows more than two stations to share a channel, some method of dealing with contention between stations is required. Some procedures are required to schedule the channel equitably between stations yet provide maximum throughput and minimum delay. These procedures are normally referred to as Protocols.

Packet Protocols:

Packet radio protocols fall into three major categories:

1. POLLING
2. TOKEN PASSING
3. CSMA - Carrier Sense Multiple Access

Polling: Polling protocols, which are the oldest, require a master station to do the polling and control the network. Polling is best suited to the systems where continuous updates of status are required at fixed intervals in time. There are two types of polling: [9]

Roll-call polling
Hub-polling

The performance of polling schemes degrades with an increase in polling overhead and hence a careful choice between the two polling schemes should be made.

Roll-Call Polling: The primary station acts as the master which cyclically polls all secondary stations for messages. The secondary station responds by sending data if its buffer is not empty. Otherwise it responds with a negative ACK. The primary station then polls the next secondary station, and so on.

Hub Polling: The primary station starts the polling process. The primary station polls the farthest secondary station to start with. This secondary station after transmitting its data, sends a poll to the next secondary station. In this polling method, the secondary stations are effectively involved in the polling process. Hub polling provides a faster response time. Network for high-rise buildings implementing hub polling provides less transmission delay and hence hub polling is chosen for our design. Hub polling is the choice in this design.

Token Passing: Token passing protocols don't require a master station. Token passers are normally configured in a ring and some complexity is involved in determining which station initiates the token either at start up or after a token is lost. Token passing protocols are popular for local area networks operating at high speeds over cables of very short lengths.

Carrier Sense Multiple Access: CSMA is a stocastic process. It requires no polling and no token. If a station has traffic to offer to the channel it will sense the channel. If the channel is free the station will transmit its data and await an acknowledgment. If the channel is in use, it will wait for a random length of time before sensing the channel again. This delay is usually measured in milliseconds. The carrier sensing reduces conflicts between station. However, conflicts can still arise and packets can overlap on the channel.

Buffering:

There are times when a packet station will not be able to forward its data from its input port to its output because it is waiting for a poll or a token or sensing the channel, depending on the protocol. It is necessary that data be stored for subsequent transmission. Also, buffering is essential when devices attached to the network operate at a speed that is different from the network itself.

In summary, packet radios are attached to a host computer (acting as a central controller), floor concentrators, and sensors. In addition, store and forward radio repeaters are provided in the network. Radios required for this network are ones with features such as fast turn on characteristics, built in modem, integral transceivers, built in power supply, and the necessary digital section containing the microprocessor controller, semiconductor memory for packet buffering, and communication software. Every unit attached to the radio in the network is required to meet certain functional requirements which are discussed in the following section.

3.2.2) FUNCTIONAL REQUIREMENTS FOR EACH UNIT IN THE NETWORK:

When the event, earthquake or strong wind, occurs, the central controller sensing the event, sends out a message to all sensors to capture data. This message is transmitted by the store and forward repeaters to each floor concentrator which in turn transmits the message to the sensors on its floor. In this way, all sensors can be activated with a minimum amount of delay. A discussion on the delay involved in packet transmission is in the next section. At the end of an event, the floor concentrator polls its floor sensors for collection of data captured during the event. The floor concentrator stores the data in its buffer. The central controller sequentially polls the floor concentrators for data. As mentioned earlier, the polling method used by the concentrators and the central controller are known as hub-polling. A polling message from the central controller reaches the floor concentrators via the store and forward repeaters. Sensors are required to record the event for a period of 10 to 15 minutes. Polling for collection of data takes place only at the end of the event.

Functional Requirements of Repeaters - Store and forward operation:

Packets from the floor concentrators reach central station by store and forward operation. In addition, packets from the central station reach the floor concentrators by store and forward operation using the radio repeaters. The radio section of the concentrator transmits the packet to its floor level repeater. It is possible that the repeaters at other levels may hear the packet. Thus it is necessary that the packet carries an identification for the intended repeater so that the other repeaters will discard the packets that are not intended for them. The repeater that is identified by the packet will relay the packet to the next repeater in the backbone. Thus the packet will be relayed from repeater to repeater through the backbone until it arrives at the final repeater which in turn sends the packet to the central station. In general, the backbone repeaters receive packets from their floor level concentrator as well as packets from the adjacent repeaters (upstream and downstream) for relay. Repeater at level (i) accepts packets from concentrator at i and packets from repeaters at (i+1) and (i-1) but not simultaneously. [10]

At each repeater, the packet is stored in memory until a positive acknowledgment is received from the next repeater or a time-out occurs. In the latter case, the packet will be retransmitted. A repeater which has just transmitted a packet should enter receive mode to listen for acknowledgment. (Half duplex operation). Half duplex operation refers to the transmission of packet in one direction only. Packet cannot be transmitted as well as received simultaneously by the repeater. That is, the repeater can either transmit or receive at a particular instant. As mentioned earlier, a repeater could have a buffer of upto 4- 6 packets. If, however, a packet arrives during the time-out period, (the period in which the repeater is in receive mode for acknowledgment), the repeater will not accept the packet if there are no unoccupied buffers in its memory.

During an event, the required mode of operation is known as broadcast to all networks. In this mode of operation, every repeater in the network keeps a short list of packet identifiers for previously broadcast packets that it recently received and transmitted. The use of this list prevents any packet from returning to portions of the network through which it has already passed. In this mode, the central station sends a message to all concentrators asking them to capture data. Subsequently, the concentrator which acts as a floor controller broadcasts this message to its sensor radios.

Functional Requirements of Concentrator:

Concentrators at each floor effectively smooth out data flow at the floor level. Unlike a multiplexer, with a concentrator, a number of input channels share a smaller number of output channels. Half duplex operation is required.

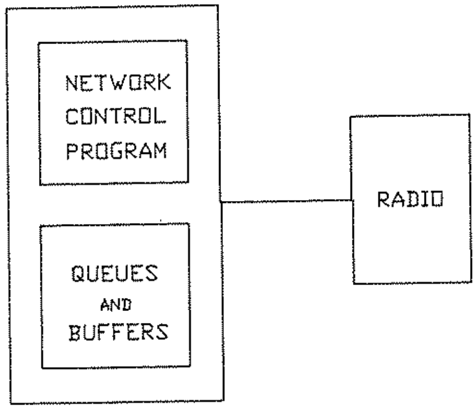

Fig (12) Floor Concentrator

In our application, the concentrator required is one which is capable of the following functions:

1. An interface message processor
2. Message storage and forward to its level repeater
3. As a polling control station to its floor radios
4. Polling all sensors on its floor in cyclic order and collecting data for buffer storage.

When a concentrator receives a broadcast poll message from the central controller at the time of an event, it identifies the packet (as the packet is meant for all floor concentrators) and broadcasts the polling message to its radios. At the end of event (which is not more than 15 minutes), the concentrator again polls its radios for collection of data and stores them in its buffer. When the central controller decides to collect the recorded data, it polls the farthest concentrator N. The concentrator N, upon receiving the poll from the central controller identifies the poll (which carries only its address) and transmits the data to the central controller. At the end of transmission of data, it passes the central controller's poll message to the next floor concentrator N-1, through its floor level repeater. [11]

Functional Requirements of Central Controller:

There is a central transceiver attached to the central computer resource - for instance a main frame host computer. This central controller controls the network, polls each floor and collects data. As can be seen in the figure (13), the controller contains communication software in order to control the network.

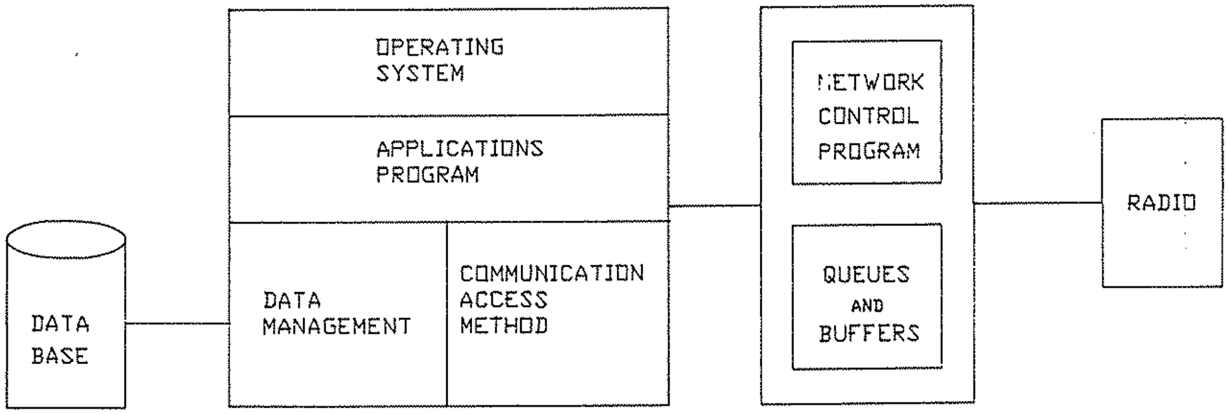

Fig (13) Central controller

The major component that is contained by the network control program is the input/output module which performs data link control. Data link control is established by the central controller using the method of polling.

Responsibilities of the central controller can be divided into two main categories:

1) To trigger the sensors with a minimum delay at the time of an event.
2) To collect sensors' data for data base.

At the time of an event, the seismic trigger or the anemometer response act as the input to the central controller, and cause the central station to start the polling process. At this time, a broadcast poll is sent to all floor concentrators through the radio repeaters. In order to collect data from the sensors after the event, the central station initiates polling the farthest floor concentrator. Since for earthquake events, the central station is located in the basement, floor concentrator N at the top floor will be polled by the central station. Floor concentrator N after transmitting its data, sends a poll to the next floor concentrator N-1 through repeater N. This polling process refers to the hub polling discussed earlier. A full duplex operation of the central station is required to carry out this operation.

For reliability, it is worthwhile to consider a system with dual central controller stations. In general, one station assumes the active role and the other station is kept informed about the status of the network. In case the active station fails, the other takes over and controls the network. The switch-over should be done in such a way that no data are lost.

CHAPTER 4

NETWORK PERFORMANCE ANALYSIS

Two major parameters are considered to be the measure of performance of the network: [12]

Delay that occurs in packet transmission
Throughput

Calculation and discussion of these parameters are the thrust of this chapter.

4.1) THEORETICAL CALCULATION OF PACKET TRANSMISSION DELAY:

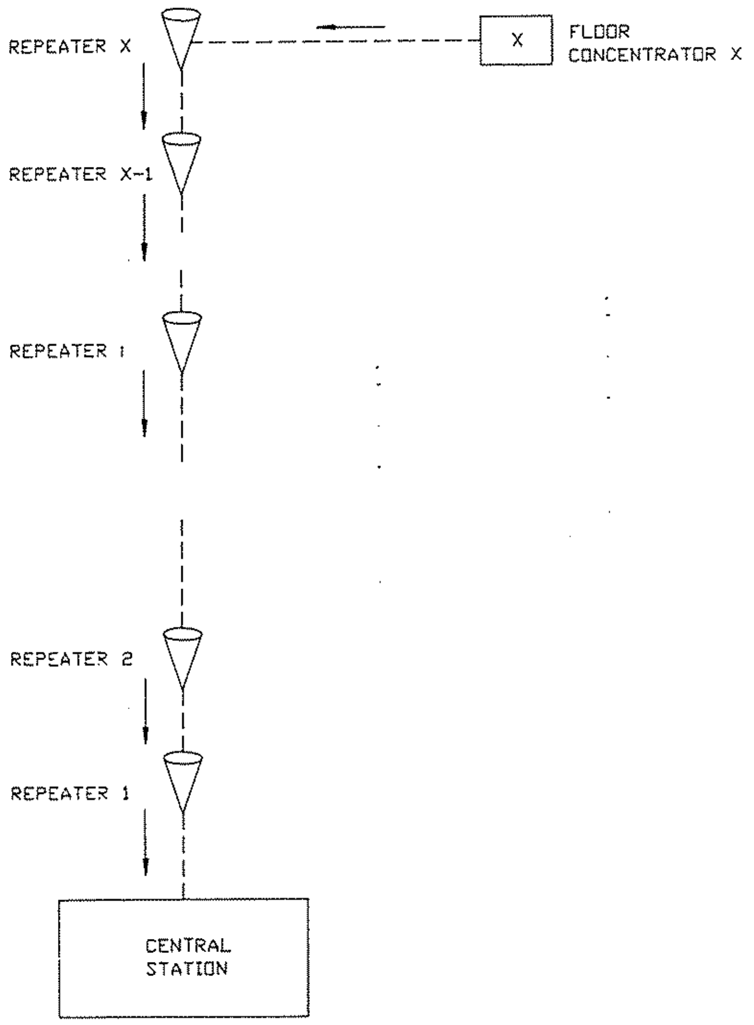

Fig (14) Packet Flow from floor concentrator X to the Central station

Packets originated at the central controller or at the floor levels incur delay before they reach their destination. By looking at the system structure shown in fig (14), it can be seen that the delay occurs at every floor i.e., floor concentrator at floor x, upon receiving the poll from the central controller, sends its packet and this packet has to go through x repeaters before it reaches the central controller. Similarly, data from the central controller destined for floor x has to go through x repeaters to reach floor concentrator x. There is delay involved in each packet transmission and the maximum delay associated in packet transmission would be for a packet transmitted to the top of the building (Floor level N) from the basement or from the top to the basement of the building. Figure (14) depicts this.

Packet transmission delay for a single hop:

A packet originated from the central controller reaches the repeater at floor level 1 and this transmission is known as a single hop transmission and delay incurred for this single hop is considered below. The successful transmission of a packet from the central controller to the repeater at level 1 is influenced by

1. the transmission of a packet from the central controller to the repeater at 1.
2. the transmission of acknowledgment from repeater 1 to the central controller.

If both 1 and 2 are successful, then the transmission is considered to be successful. If either 1 or 2 fails, the message must be retransmitted.

Calculation of transmission delay for a single hop:

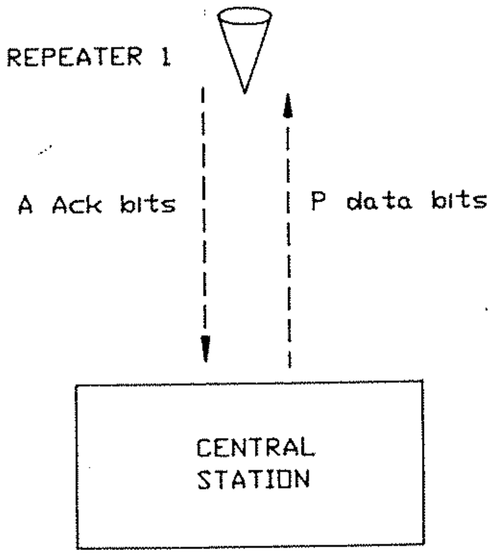

Fig (15) Packet transmission between the Central Station and Repeater at Floor Level 1

P - # of bits in a data packet which includes both data bits and overhead bits.

A - # of bits in an acknowledgment packet.

C - # of bits/second at the channel rate. (capacity of the channel).

d - time which includes propagation delay, switching time (modem delay) and checksum computation.

Probability of loss of a packet:[13]

Packet loss can occur during either

1. the transmission of a packet from the central controller to the repeater at 1.

or 2. the transmission of ACK from repeater 1 to the central controller.

We assume packets consisting of data packets and acknowledgement packets and introduce,

L = probability of loss of a packet,
L_p = probability of loss of a data packet
L_a = probability of loss of an acknowledgment packet

L can be written as

$$L = 1 - (1 - L_p) * (1 - L_a) \qquad \text{Equation [1]}$$

where $(1 - L_p)$ is the probability that a data packet is not lost
and $(1 - L_a)$ is the probability that the ACK packet is not lost.

Mean number of retransmissions required for successful transmission: [14]

Let K be the number of retransmissions required for a successful transmission.

$$\text{Mean } K = \frac{L}{1 - L}$$

As shown in figure (15), number of data bits per data packet is P and number of bits per acknowledgement packet is A. Time zero is taken to be the time at which the central controller starts transmission of the data packet. The time taken by the central controller to transmit a data packet is P/C seconds where C is the transmission capacity of the channel in bits per sec. Because of the channel transmission delay, the repeater 1, finishes receiving the packet by time $(P/C)+d$. The repeater 1, begins sending the ACK packet of length A bits at time $(P/C) +d$ and finishes transmission at time $(P/C) + d + (A/C)$. This ACK packet reaches the central controller at time $(P/C) + d + (A/C) + d$. Thus ends a successful acknowledged transmission cycle.

Time out period:

Time out period T is the time the central controller waits before retransmission. At the end of the time out period, the central controller retransmits the packet if no acknowledgement/ACK has arrived. From the packet sequence number, the repeater at level 1 identifies whether it is duplicate or new. Time out period can occur due to loss of either the data packet or the acknowledgment packet. If time out occurred due to loss of the ACK, then the data packet retransmitted by the central controller to repeater 1 would be a duplicate packet. If the time out period occurred due to loss of the data packet, then the packet retransmitted by the central controller would not be a duplicate packet at repeater 1. Repeaters identify the packets as duplicate or new, and duplicate packets are discarded at the repeaters. T should be equal to or greater than 2d + (A/C).

$$T >= 2d + A/C. \qquad \text{Equation [2]}$$

By defining t_i as the time taken for an acknowledged cycle with number of retransmission K equal to i, we get mean transmission time

$$t = [\ (P/C\ ) + 2d + (\ A/C\ )\ ] + [\ L\ /(\ 1 - L\ )\ ] * [\ (P/C\ ) + T\ ]$$

This mean transmission time can be used as a measure of effective delay between the central controller and the repeater 1. In addition, this equation holds for any single hop in the network.

Calculation of mean transmission time required for the packet to reach the repeater at the top of the building:

Let D be the time required to travel between the central controller in the basement and the repeater at the top of the building. Since d is the time required for a single hop, D/d is the number of circuit hops used before reaching the destination. In a practical sense, D/d is the story height of the building where there is a repeater on each floor.

HOP BY HOP ACKNOWLEDGED TIME DELAY:

$$t = (D/d)*\Big[[(P/C)+2d+(A/C)] + [L/(1 - L)] * [(P/C\ ) + T]\Big] \qquad \text{Equation [3]}$$

By substituting the minimum value of T from equation [2],

$$t = (D/d) * [1/(1 - L)] * [(P/C)+2d+(A/C)] \qquad \text{Equation [4]}$$

Note: P/C = Data packet transit time
2d = Round trip propagation time
A/C = Acknowledgment packet transit time
T = time out period (Minimum value = Acknowledgement packet transit time + round trip propagation time)
>= 2d + (A/C)

D/d = number of floors and equals the number of repeaters

4.2) THEORETICAL FACTORS AFFECTING THROUGHPUT OF THE NETWORK

Definition of throughput: Throughput S is the normalized rate of data packets successfully transmitted. In other words, throughput is the effective capacity and is calculated by taking the ratio of number of data bits transmitted in a packet to the mean time for a successful, acknowledged packet transmission. [15] Using equation [3], we get

$$S = \frac{R}{(D/d) * ([(P/C) + 2d + (A/C)] + [L/(1 - L)] * [(P/C) + T])}$$

where

R - number of data bits in a packet and
P - number of bits in a packet which includes data bits and overhead bits.

Looking at the expression for S,

- if R << P, then throughput is overhead limited,
- if channel capacity C is small to make P/C and A/C large in the denominator of the above equation, then throughput is capacity limited,
- if switching delay 2d dominates, then throughput is delay limited,
- if probability of loss of a packet L is high, then throughput is error limited,
- if number of hops D/d is large, then throughput is distance limited.

By substituting the minimum value of T from equation 2, throughput becomes:

$$S = [1/ (D/d)] * (R/P) * (1 - L) * C * [P / \{ P + (C * [2d + A/C]) \}]$$

$$= [1/ (D/d)] * (R/P) * (1 - L) * C * [P / \{ P + (C * T)\}]$$

One can see from the above equation that the throughput is the product of five factors: (Hereafter T = 2d + A/C , the minimum from equation #2.)

1. an overhead factor (R/P)
2. a distance factor (D/d)
3. an error factor (1 - L)
4. an efficiency factor $E = P/\{ P + (C * T)\}$
5. a channel transmission factor C

All the factors except the efficiency factor have a clear impact on the throughput of the network. A review of the efficiency factor is shown below:

$$E = P/\{ P + (C * T)\}.$$

C * T is the number of bits that could be transmitted over the channel while waiting for an acknowledgment to a previous P bit packet. P/ {P + (C * T)} is the ratio of the number of bits in a packet (P)to the number of bits which can be transmitted during the acknowledgement waiting time (C * T). Thus, E indicates a factor of different packets that could be pending at once and throughput S is proportional to E.

4.3) END TO END ACKNOWLEDGMENT:

Packet transmission delay for one cycle: A packet originated from the central controller has to travel D/d hops to reach the repeater at floor level N and the acknowledgement from the repeater N has to reach the central controller after going through D/d hops. The successful transmission of a packet from the central controller to the repeater at level N, involves both i) the transmission of a packet from the central controller to the repeater at N and ii) the transmission of acknowledgment from repeater N to the central controller.

Probability of loss of a packet: The analysis is similar to that for a loss within a single hop. Packet loss can occur either during

1. the transmission of a packet from the central controller to the repeater at N level or during
2. the transmission of ACK from repeater N to the central controller.

By introducing,

L - probability of loss of a packet in one end to end ack cycle,
L_p - probability of loss of a data packet in one hop,
L_a - probability of loss of an acknowledgment packet in one hop,

$(1- L_p)$ is the probability that a data packet is not lost and $(1 - L_p)^{D/d}$ the probability that a data packet is not lost in one cycle and

$(1 - L_a)$ is the probability that the ack packet is not lost and $(1 - L_a)^{D/d}$ is the probability that the ack packet is not lost in one cycle

L can be written as

$$L = 1 - (1 - L_p)^{D/d} * (1 - L_a)^{D/d} \qquad \text{Equation [5]}$$

END TO END TIME DELAY:

Mean transmission time t is :

$$t = [1/(1 - L)] * (D/d) * [(P/C) + 2d + A/C] \qquad \text{Equation [6]}$$

4.4) HOP BY HOP VERSUS END TO END ACKNOWLEDGMENT:

Hop by Hop mean transmission time derived in equation [4]:

$$t = (D/d) * [1/(1 - L)] * [(P/C)+2d+(A/C)]$$

Substituting the value for L from equation [1]

$$t = (1/[(1 - L_p)*(1 - L_a)]) * (D/d) * [(P/C) + 2d + A/C] \qquad \text{Equation [7]}$$

End to End mean transmission time derived in equation [6]:

$$t = [1/(1 - L)] * (D/d) * [(P/C) + 2d + (A/C)]$$

Substituting the value for L from equation [5]

$$t = (1/[(1 - L_p)^{D/d} * (1 - L_a)^{D/d}]) * (D/d) * [(P/C) + 2d + (A/C)] \qquad \text{Equation [8]}$$

Comparing mean transmission time for hop by hop acknowledgement in equation [7] with the mean transmission time for an end to end acknowledgement shown equation [8], we can see that the difference is in the denominators.

In end to end acknowledgment,

$(1 - L_p)$ and $(1 - L_a)$ are raised to the power of D/d .

Since $(1 - L_p) * (1 - L_a)$ is much greater than $(1 - L_p)^{D/d} * (1 - L_a)^{D/d}$, mean transmission time in hop by hop acknowledgement is smaller than end to end acknowledgement. This may be seen from the ratio of hop by hop to end to end acknowledgment.

$$\frac{\text{Hop by Hop mean transmission time}}{\text{End to End mean transmission time}} = (1 - L_p)^{(D/d)-1} (1 - L_a)^{(D/d)-1} < 1$$

where $0 <= L_p <= 1$

$0 <= L_a <= 1$

Therefore hop by hop mean transmission time is less than end to end transmission time.

The factors that discriminate the choice of hop by hop or end by end acknowledgment are:

1. number of hops D/d
2. probability of loss of packet L

Hop by hop ACK should be implemented when D/d is large and when L is not negligible. Thus, the hop by hop ACK is superior to end by end ACK when many hops are required and with a non negligible L.

CHAPTER 5

CONCLUSIONS

This report has presented a network design for integrating information sensor outputs in high-rise buildings. Specific application would be to monitor earthquake and wind effects. The network design is capable of transmitting data from all floors of the building. At the time of an event, sensors at all floors can be initiated with a minimum delay which makes it possible to have simultaneous recording of all sensors.

The following values have been assumed for the network designed in order to get typical values for the maximum delay involved.

Channel transmission capacity, C - 10 Mbps
Number of bits in a data packet, P - 9900 bits
Number of bits in acknowledgment packet, A - 100 bits
Switching delay, propagation delay and checksum computation time, d - 1 millisec

Note: With the above values of 9900 bits data and 100 bits ACK, the protocol contains approximately 1% overhead.

Substituting the values for C, P, A , and d in equation 4 and equation 6, we obtain

$$\text{Hop by hop delay} = (D/d) * [\,1/(1 - L)\,] * 3 \text{ msec}$$
$$\text{End to end delay} = (D/d) * [\,1/(1 - L)\,]^{D/d} * 3 \text{ msec}$$

By looking at the expression for delay, it can be seen that the delay in packet transmission is influenced by two factors - story height of the building, D/d, and the probability of loss of a packet, L.

Effect of L on the packet transmission delay:

Assuming L is negligible, delay is dictated only by the story height of the building multiplied by 3 millisec. Also delay involved in hop by hop and end to end turns out to be the same with negligible L. For a 50 story building, the delay is approximately 150 msec; for a 100 story building the delay becomes 300 msec. If L is non-negligible, delay increases and is still in the msec range.

With L as high as 0.01, the delay involved in a 50 story building is approximately 150 millisec and 300 millisec for 100 story building for hop by hop transmission. End to end delay with L as 0.01 is 250 millisec for 50 story and 820 millisec for 100 story building. Thus, hop by hop is superior assuming non negligible L and D/d > 1.

Period of Vibration:

High-rise buildings have frequencies of vibration depending on their size and construction. The period of vibration of a high-rise building subjected to any geological events increases with the height of the building. The fundamental period of a 50 story building subjected to earthquake ground motions is as high as 2.5 sec. The expected value for a 100 story building is 5 secs or higher. The building response is slower as the height increases. The maximum delay for a 100 story building, even with a value of L as high as 0.01, is calculated as 300 millisec (0.300 sec). Thus, the delay in activating the sensors at the time of an event is less than one tenth the period of the vibration being measured and is felt to be acceptable.

Technology is still being explored to monitor events such as earthquake and wind in high-rise structures. With miniaturization of electronics and the development of intelligent sensors, information gathered from large numbers of such devices can be used to better understand current structural behavior and prevent failures. The sensor information must be sent to a facility where the processing takes place. The management of this transmission is a protocol.

Performance of this network was analyzed in order to ensure that there were no excess delays in the trigger signal. If there were, the leading edge of the data may have been lost. It was found that with this scheme, hop-to-hop acknowledgment technique was superior to end-to-end, under the constraints such as the number of sensors, number of floors, and probability of transmission errors.

This protocol is one of the building blocks in integrating intelligent sensors of the future. It may be economic in the very near future to incorporate the remainder of the sensory and analysis requirements as well as protocol and transmission of this information to other sensors and computers on a handful of chips. Many of the rest of the entire system such as instrumentation amplifiers, analog to digital converters, and radio frequency transmitters and receivers are well established and miniaturized. The time has come to integrate these individual functions into a small and economical package. With this capability accurate and timely information can be acquired from real structures under actual conditions. This may lead to better understanding of structures under adverse conditions which may in turn lead to better reliability.

REFERENCES

1. Beedle, Lynn. S., High-rise Buildings: Recent Progress.
   Stroudsburg, PA: Hutchinson Ross Publishing Co., 1986.

2. Mitchell, G. R., "Loadings on Buildings" Proceedings on International Conference on Tall Buildings and Criteria, Vol. 1b (1973), pp 19-40.

3. Special Issue on Sensors. Honeywell, 1987.

4. Walton, W. W., and Cadoff. B. C., Performance of Buildings Concept and Measurement. Building Science Series 1, National Bureau of Standards, 1970.

5. Stallings, W. Tutorial- Local Network technology.
   IEEE Computer Society., 1984.

6. Acampora. A. S., and Winters, J. H., "A Wireless Network for Wideband Indoor Communications" IEEE Journal on Selected Areas in Communications,Vol. SAC-5, No 5, (1987), pp. 796-805.

7. Stallings, W., Data and Computer Communication. 2nd ed.
   New York, Macmillan Publishing Company., 1988.

8. Data Radio Corporation, Atlanta, GA.
   Data Radio Features (1984).

9. Tanenbaum, A. S., Computer Networks.
   New Jersey: Prentice Hall Software Series., 1981.

10. Khan, R. E., "The Organization of Computer Resources into a Packet Radio Network" IEEE Transactions on Communications, Vol. COM-25, No. 1. (1977), pp. 169-178.

11. Katzan, H. An Introduction to Distributed Processing.
    Petrocelli Books, Inc., U. S. A. 1978.

12. Stallings, W., "Local Network Performance" IEEE Communications magazine, Vol.22. No. 2, (1984) pp. 27-36.

13. Metcalfe, R. M., "Packet Communication" Tech. Rep., MAC TR 114, Project MAC, Massachusetts Inst. Technol., Cambridge, (1973).

14. Ross, S., Introduction to Probability Models.
    New York, Academic Press., 1972.

15. Abramson, N., "The Throughput of Packet Broadcasting Channels" IEEE Transactions on Communications, Vol. COM-25, no. 1, (1987), pp. 117-127.