# HIGHLY SYNCHRONOUS COMMUNICATION – CHARACTERIZATION, MODELING AND CONTROL

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Submitted to the Graduate Faculty of

Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2008

UNIVERSITY OF PITTSBURGH

SWANSON SCHOOL OF ENGINEERING

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# HIGHLY SYNCHRONOUS COMMUNICATION – CHARACTERIZATION, MODELING AND CONTROL

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University of Pittsburgh, 2008

There exists a class of systems with requirements for real-time data delivery, limits on end-to-end delay, and limits on jitter. These systems can have components distributed across a wide area. In addition, the components distributed across a wide area require that the arrival and departure of data occur synchronously. To support these classes of systems, the communication systems must be able to transmit the required information within a pre-determined window of time. Due to the synchronous nature and requirements of these classes of systems, they are referred to as being Synchronous Dependent (SD).

This research models and characterizes a serial communication link for application in a strict time constraint environment. These applications will also have limitations on jitter and delay, relative to the need to synchronize with other components of the system. Additionally, the research provides the modeling of users that utilize applications with relaxed constraints. The communication link will be able to support multiple users with varying requirements, from highly periodic control data to aperiodic general data.

The network link is a modified T-channel, with resource reservation applying to both bandwidth and size allocation of a data frame. In contrast to a standard T-channel, the link has adjustable channel sizes, as well as the capability to shift a transmission out of the assigned channel into a channel either earlier or later than the previously assigned channel. In addition, a user may use more than one consecutive channel for the transmission of a single instance of

information, i.e., multiple channels can be viewed as concatenated for use by a single user. The purpose of the channel is to provide a dedicated time slot available to the user that needs to transmit at a specific time that is also periodic.

Through the modeling of the user's communications across the link, it is possible to examine the potential effects of the various characteristics of the individual user on the other users requesting access to the link.

Assuming no adverse affects and to insure that time sensitive data are delivered on time, a method to determine the acceptability of the admission of the given user has been designed to determine which users will have access to the link and those that will not.

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# PREFACE

I would like to my wife Janet for her patience, encouragement, and assistance, and my children Jessica, Julia, and Joshua for their allowing me the time to do this dissertation.

I would like to thank my parents, brothers, sisters, nieces, and nephews for their support.

To my friends at Geneva College for their support and the College's support of my work, thank you.

To the members of my committee, thank you for your willingness to participate in this endeavor.

To Professors Mickle and Cain, there is nothing I can say or do to express my gratitude for your long-running support, guidance, perseverance, understanding, wisdom, and assistance in my work and your devotion to your profession.

And to the Lord Jesus Christ, for providing all of the people above, for without them I would not have been able to persevere. This dissertation is in His honor.

# 1.0 INTRODUCTION

Data communication networks are used to transmit voice, video, data, and pictures. Some of these classes of applications have no requirements as to whether the transmitted information can arrive out of sequence. Some of these applications may also have no requirements on the amount of delay between the sending and receiving of the transmission, or on the variation of delay. Other classes of these systems have restrictions on the order of delivery of the information, how much delay is acceptable, and how much jitter is permissible. The classes of systems with restrictions on jitter, delay, and order of delivery are called Synchronous Dependent (SD) systems. The characterization and modeling of the Synchronous Dependent communication systems used to support these latter systems and the users of these systems is the focus of this dissertation. An example of an SD system is a classical real-time control system.

## 1.1 REAL-TIME AND SYNCHRONOUS DISTRIBUTED SYSTEMS

A real time system requires that the operation requested occur at the required time and with the correct result. For the operation to occur at the required time, the delay and the jitter cannot be greater than the bounds specified by the user's requirements.

Real-time systems can be further classified into hard real-time and soft real-time systems. A system that will experience severe consequences if the "logical as well as timing correctness properties of the system are not satisfied"[1] is a hard real-time system. A soft real-time system will have fixed deadlines and requirements similar to a hard real-time system but will not have the severe consequences if the user's requirements are not satisfied.

The components of the hard real-time system need not be located in proximity to one another. Such a system is called a distributed system. The components of the distributed real-time system will communicate over a private or a shared communication link. The distributed system increases the probability that there will be delay and jitter in the transmission of information from each source to each destination.

The use of distributed systems also introduces other possible service requirements to support the system. Since the components are not in proximity to one another, and since the system requirements are such that operations must occur at specific times relative to one another, synchronization to a real-time clock may be required. These systems may also have multiple distributed locations that require the synchronization of sampling and the application of control data at specific times.

The Synchronous Dependent communication system used to support distributed systems with hard deadlines and delay and jitter requirements must be able to guarantee the delivery of the transmitted information. In addition, the Synchronous Dependent communication system must be able to restrict users from utilizing the link that will adversely affect those users that have already been admitted and are currently using the SD link.

## 1.2 QUALITY OF SERVICE AND ADMISSION CONTROL

Each user of the SD communication system could have requirements as to the amount of bandwidth necessary for the transmission of data, the frequency of transmission, the delay allowed for each transmission, the variation in delay (jitter) that can be supported, the loss of data that can be tolerated, or any combination of these. Additionally, the duration of transmission by a user will affect the ability of the communication system to support other users. This type of information is the Quality of Service requested by a user.

For hard real-time systems, the strict limits on the delay, jitter, and loss require that the communication system must be able to provide an environment to support zero loss, possibly zero jitter, and fixed delay. Communication systems that provide all users with the same level of service and are not able to provide guarantees for delay, loss, throughput, and jitter[2] would not be acceptable for hard real-time systems.

A method to determine the alternatives of admitting any given user will determine whether there are sufficient resources available for the user requesting access to the link, whether the user requesting access provides the best use of the link resources, and whether the requesting user is compatible with the other users that have already been granted access to the link. The admission control will also act as the scheduler of the user transmissions, as it also will be used to determine when a user may transmit.

The admission control methodology will have to evaluate the user's requirements for transmission relative to the user's periodic transmissions, jitter, delay, total time of transmission (i.e., infinite or not), and relative to whether a specific time of transmission required to support synchronous requirements with other distributed systems is necessary.

It will be shown that users requesting admission to the link that are transmitting at a rate that is not a multiple of the users already in the system will impact the transmissions of other users. The method of determining admission will evaluate the impact and determine a course of action directed towards the user requesting admission.

Other variations in user characteristics will have a similar impact on existing users of the link; these will also need to be evaluated by the proposed methodology.

## 1.3 BACKGROUND

Communication systems can be divided into a variety of classifications. Some examples of these are private communication systems versus public systems, multiple-access versus single user, synchronous versus asynchronous, connectionless versus connection-oriented, circuit switched versus packet switched, fixed-length packets or cells versus variable-length packets or cells, time-division multiplexed, token-based, and other variations.

Some classes of communication systems were designed to support a particular application, while others are able to support a wide range of applications with different requirements for Quality of Service. This section is an overview of several different communication methodologies and their capability to support real-time data transfers with emphasis on characteristics that are either more or less supportive of SD systems.

In some instances, reference is made to both the Physical Layer and the Data Link Layer, which refer to their classification relative to the Open Systems Interconnect[3] (OSI) model, which was developed in 1977 by the International Standards Organization (ISO). The OSI model consists of seven layers that provide an abstract description for communications and computer network protocol design[4].

### 1.3.1 Ethernet and CSMA/CD

Ethernet is one of the most popular LAN and WAN transport services. Ethernet can transmit at 10 mbps, 100 mbps, 1 gbps, and 10 gbps and can transmit across a variety of media, including fiber and several categories of unshielded twisted pair.

Ethernet is a connectionless service, which means that a connection is not set up between sender and receiver prior to the beginning of a transmission by the sender. Ethernet also uses variable-length packets.

Ethernet uses Carrier Sense Multiple Access with Collision Detection (CSMA/CD) as the access control method to the network.

CSMA/CD provides access to a shared communications medium by:

1.) Requiring users to listen for the transmission of other users
2.) After determining no one else is transmitting, the user may transmit his data
3.) If a collision occurs, users will continue to transmit to ensure all stations on the network are aware a collision occurred.
4.) All stations stop transmitting for a random amount of time
5.) After the waiting period, the station attempts to retransmit.[5]

The components of the CSMA/CD access policy are:

1.) A station begins to transmit its data.

2.) After the collision window has passed, the station is said to have acquired the medium. The collision window is the time for the transmitting station's signal to propagate to all other stations on the medium

3.) Subsequent collisions are avoided as all properly operating stations will not transmit due to the carrier sensing of the transmitting station's signal.[6]

The operating environment for the CSMA/CD standard is Local and Metropolitan networks, as discussed in the IEEE 802 standard.

With respect to the characteristics for SD and hard real-time control systems transmitting over an Ethernet network, CSMA/CD does not have a means to provide resource reservation, which is needed to guarantee resources to a user. The delay associated with a CSMA/CD network is not predictable given that any station on the network can transmit at any time. If it was necessary to transmit time-sensitive information on a network operating with CSMA/CD, there is no guarantee that the user could transmit at the desired time. This addresses two other characteristics of SD networks that are not available in the CSMA/CD environment: the capability to handle time sensitive data and guaranteed transmission slots. The admission control of CSMA/CD is not able to control delay and does not have the capability to regulate the transmission of time-sensitive data. The connection request procedure to transmit across the network is essentially listening to the network to see if anyone else is transmitting. If no other station is transmitting, it is OK to transmit. This does not assess the needs of the other users of the networks before the admission to the network. Admission control to the network is again a manual operation, achieved by connecting a device to the network.

As such, Ethernet using CSMA/CD does not have the characteristics required to support a network to be used for real-time transmissions.

### 1.3.2 Token ring and token passing

The IEEE Standard 802.5-1989 is the standard for token passing in a ring. Token ring is a connectionless, variable-packet length service. Shown below is a representation of eight computers connected in a ring, using the token passing media access control.

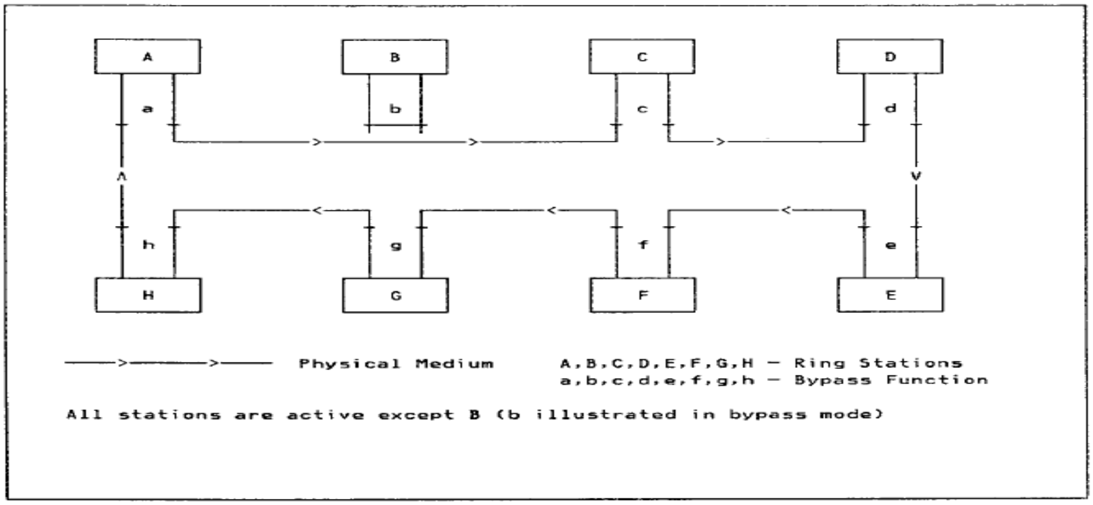


**Figure 1.1. Token Ring Configuration**[7]

The Token Ring Access method provides access to a shared communications medium when a station:

1.) Waits for the token to become available on the ring
2.) Removes the token from the ring
3.) Places its data on the ring and the data is transmitted around the ring
4.) The receiving station copies the data off the ring
5.) After the data returns to the originating station, the data are removed form the ring and the token is passed on.[8]

Without any levels or prioritization, the availability of a transmission window is based on the time associated with the token holding timer, $\boldsymbol{\tau}_{THT}$, and the number of stations on the ring, $\boldsymbol{\eta}$. Ideally, a station on the ring will transmit every $\boldsymbol{\eta}$ divided by $\boldsymbol{\tau}_{THT}$ periods of time. In reality, this is a maximum time a station on the ring will have to wait before transmitting. It does not guarantee that a station will transmit every $\boldsymbol{\eta}$ divided by $\boldsymbol{\tau}_{THT}$ periods of time.

There are at least two occurrences that would affect the time when a station would be allowed to transmit. The first occurrence would be when a station has nothing to transmit. The station sees the token and does not take it off the ring. The other occurrence is when a station does not utilize the full time allotted by the token holding timer. If the station that was transmitting only utilizes half of $\boldsymbol{\tau}_{THT}$, then the token will reach the other stations $\boldsymbol{\tau}_{THT}/2$ time periods faster than it normally would. Delay and jitter are also a functions of the speed of the terminal. In either of these situations the data may not be ready to be transmitted when the station has the token, and the station would have to wait until the token goes around the ring again.

Token passing does support priority requests to transmit, which limits access to the ring to those stations that need more access to the ring. When a station needs to transmit, the priority on the token is changed such that only stations with an equal or higher priority than the priority placed on the token could transmit. However, this means that any station with the right priority could transmit, not just the one that set the priority on the token.

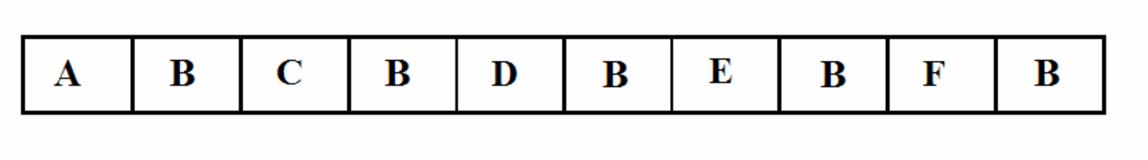
Those users with the higher level of prioritization would equate to an SD user. The prioritized traffic is the concept that is the one of the bases for SD. However, raising the level of a group of users does not necessarily equate to having a dedicated channel for a prioritized transmission, which is what SD proposes to provide.

With respect to the network characteristics presented previously, token passing does provide the capability for a node on the network to reserve the token. However, another machine with a higher priority can supersede the reservation and take the token. While this does provide a form of resource reservation, what is missing is a centralized control for the reservation of resources.

The delay associated with token passing networks can be predicted as long as prioritization of resources is not used, as is discussed above. With prioritization, delay becomes unpredictable.

Jitter is defined differently for the 802.5 standard than it is as a network characteristic. In relation to the network characteristics definition, the token passing network could have definable jitter requirements if the maximum transmission time is used on all stations.

Token passing's use as an SD communications methodology is limited also by the architecture of the network. If a node in a token passing ring needed to transmit every other transmission time, as shown below, token passing would require that the token pass around the ring every time and that the priority for the token be set such that station B could transmit as needed.



| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| A | B | C | B | D | B | E | B | F | B |

Figure 1.2. Sample Traffic Pattern in a Token Ring Environment

What is missing from the Token Access methodology is the ability for the admission control methodology to determine in advance what message will be sent at a particular time, i.e., the scheduling in advance of both resources and transmission times. This includes a predetermination of the size of the message being sent.

Therefore, token passing would not qualify as an SD communication network.

### 1.3.3 Frame relay

Frame Relay can be viewed as a precursor to Asynchronous Transfer Mode[9], which will be discussed in Section 1.3.6.

Frame Relay is a connection-oriented transmission scheme that sets up a virtual path from sender to receiver. Frame relay transmits packets of variable size up to 4096 bytes.

A Frame Relay service consists of Committed Information Rate (CIR) that guarantees a throughput. Frame Relay can additionally be configured to provide the capability to burst (burst rate, br) to twice the capacity of the subscribed link.

Frame Relay also supports both Forward Explicit Congestion Notification (FECN) and Backward Explicit Congestion Notification (BECN) to allow users to scale back transmissions in the event of congestion elsewhere on the network.

Two particular aspects of Frame Relay are detrimental to the support of real time data transmissions. First, the ability of the user to burst to twice the Committed Information Rate will introduce the very congestion that the FECN and the BECN are providing information about. This will affect the capability of the network to support those users that require a fixed transmission rate. Second, the fact that Frame Relay can transmit packets of variable size introduces the possibility of jitter.

In support of SD data transmissions, the connection-oriented service provided by Frame Relay eliminates the variable transmission time associated with routing. In addition, the concept of congestion notification does provide the capability to scale back lower priority traffic in support of higher priority traffic. A better solution than congestion notification is no congestion at all.

### 1.3.4 Fiber distributed data interface (FDDI)

Fiber Distributed Data Interface (FDDI) uses a timed token-passing concept. The idea behind the timed-token rotation time is to control the token rotation time using a protocol parameter called the *target token rotation time* (TTRT)[10]. This parameter gives the expected token rotation time around the ring.

Each node is assigned a portion of TTRT, ”known as the *synchronous bandwidth*[11]”, which is the maximum time allotted to each node to transmit synchronous, time sensitive, messages every time the token comes around. To ensure that synchronous message deadlines are met, the requirement is that the network designer carefully chooses the network parameters.

An FDDI node will transmit asynchronous packets containing time-constrained data, after the node has transmitted the packets with deadlines. By using pseudo-synchronous streams for the asynchronous data, the packets are treated the same as synchronous streams. This concept of coexisting data will be a part of the reported research.

In support of real-time data transmissions, FDDI allots time for synchronous messages to be delivered across all stations on the ring. Unused synchronous time can be used by asynchronous messages. The obvious limitation is that the synchronous messages cannot require delivery in time faster than the time associated with the TTRT. If the synchronous time allotted to a node is insufficient, the message cannot be guaranteed, and if the synchronous time allotted is too much, other nodes may not have sufficient time to transfer their synchronous messages.

### 1.3.5 Distributed queue dual bus (DQDB)

The Distributed Queue Dual Bus (DQDB) is a dual bus architecture that was proposed as a sub-network on a Metropolitan Area Network (MAN). The 802.6 standard for the DQDB was withdrawn in 1993.

DQDB was designed to support connectionless data transfers, connection-oriented data transfers, and isochronous (voice) traffic[12].

DQDB is discussed here as an example since it has some features that support data transmissions that are time-sensitive.

The Dual Bus architecture of the Distributed Queue Dual Bus network consists of two unidirectional buses with nodes attached to the buses[13]. The buses operate with communications in opposite directions on the two buses.

The data on each bus is either a DQDB Management octet or a fixed length slot, generated by the node at the head of each bus. Under normal conditions there is a single source of slot timing on the sub-network, to insure that all nodes transfer data at the same average rate[14].

There are two modes of access to the dual bus network: Queue Arbitrated (QA) and Pre-Arbitrated (PA). Pre-Arbitrated slots are used for isochronous services and are used to support phone service.

In support of real time traffic, DQDB has a method of supporting prioritized traffic (PA – Pre-Arbitrated), it has fixed length slots to avoid the possibility of induced jitter from variable length packets, it is a connection-oriented service, and it has a method to support non-isochronous traffic.

A limitation of DQDB in relation to real-time support is it is only designed to support octets of data for isochronous traffic. The proposed SD link will be able to have different sized channels.

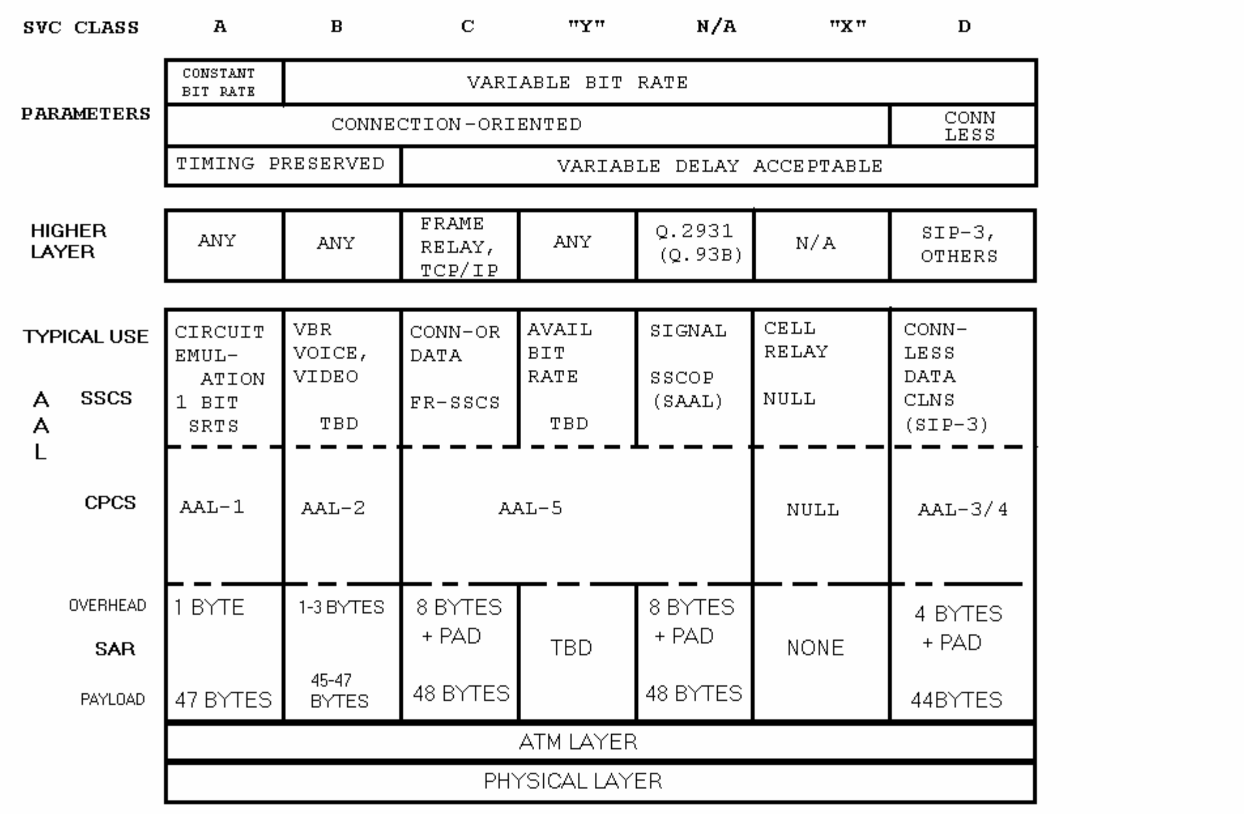
### 1.3.6 Asynchronous transfer mode

Asynchronous Transfer Mode (ATM) is a connection-oriented service in that it provides a path from source to destination prior to beginning the transmission of data. The cell size, comparable to a frame or a packet as a unit of transport, is a fixed 53 bytes, with a normal payload of 48 bytes. ATM also supports connectionless data transmissions. ATM was designed to support voice, video and data from its inception.

The ATM transmission service provides for slots, delineated by a marker at the beginning of the slot, where ATM cells can be placed if there is data to transmit. ATM utilizes one aspect of a circuit-switched network, the slot, and utilizes an aspect of the packet-switched network, the larger packet size, and combines them into the cell-switched network. ATM does not provide a guaranteed slot to a user.

ATM provides several modes of operation, or rates, to enable it to support the various applications. The available rates are Constant Bit Rate (CBR), Variable Bit Rate (VBR), Available Bit Rate (ABR), and Unspecified Bit Rate (UBR). ATM would also be able to support a user that wanted to transmit two cells in succession, in the event the data being sent was longer than the standard 48 byte payload.

Figure 1.3 shows the type of traffic ATM was designed to support.



| SVC CLASS | A | B | C | "Y" | N/A | "X" | D |
|---|---|---|---|---|---|---|---|
| PARAMETERS | CONSTANT BIT RATE | VARIABLE BIT RATE | | | | | |
| | CONNECTION-ORIENTED | | | | | | CONN LESS |
| | TIMING PRESERVED | | VARIABLE DELAY ACCEPTABLE | | | | |
| HIGHER LAYER | ANY | ANY | FRAME RELAY, TCP/IP | ANY | Q.2931 (Q.93B) | N/A | SIP-3, OTHERS |
| TYPICAL USE | CIRCUIT EMUL-ATION | VBR VOICE, VIDEO | CONN-OR DATA | AVAIL BIT RATE | SIGNAL | CELL RELAY | CONN-LESS DATA |
| AAL SSCS | 1 BIT SRTS | TBD | FR-SSCS | TBD | SSCOP (SAAL) | NULL | CLNS (SIP-3) |
| AAL CPCS | AAL-1 | AAL-2 | AAL-5 | | | NULL | AAL-3/4 |
| AAL SAR OVERHEAD | 1 BYTE | 1-3 BYTES | 8 BYTES + PAD | TBD | 8 BYTES + PAD | NONE | 4 BYTES + PAD |
| AAL SAR PAYLOAD | 47 BYTES | 45-47 BYTES | 48 BYTES | | 48 BYTES | | 44BYTES |
| | ATM LAYER | | | | | | |
| | PHYSICAL LAYER | | | | | | |

**Figure 1.3. ATM Adaptation Layer**[15]

Originally ATM was intended for use both for the Local Area Network and for the Wide Area Network. However, ATM suffered from the same thing that prevented Token Ring from becoming more widely used, which was the high cost of equipment. In addition, ATM networks are extremely complex to operate[16].

ATM provides many of the features desired to support real-time traffic. It has a fixed cell size, it provides virtual connections prior to beginning transmissions, and it has a fixed time to begin a cell transmission. The one thing it does not provide, intentionally, is a dedicated slot in support of real-time traffic.

### 1.3.7 T1 and ds1

The T1, or transmission level 1, was originally the physical media used to transmit 24 telephone transmissions simultaneously[17]. The DS1, or digital signal level 1, was the signaling scheme[18]. The two terms now are often used interchangeably. The term T1 will be used to reference both.

A channelized T1 is 24 channels of digital data being transmitted serially across the same pairs of lines. The T1 uses Time Division Multiplexing (TDM) to combine the 24 channels into one data stream. The T1 was originally used to increase the number of phone conversations transmitted between Central Offices. The T1 has a transmission rate of 1.544 mbps, which is comprised of the 24 channels of 8 bit voice being transmitted at a rate of 8000 times per second, with each 24 channels (frame) separated by a sync bit.

A channelized T1 is a connection-oriented service. It establishes a connection prior to the transmission of data. This is in contrast to a connectionless service, which is required to find the path from source to destination.

A non-channelized T1 is typically used to support connectivity to the Internet. A non-channelized T1 can be used to transmit protocols higher on the Open Systems Interconnection (OSI) model, which can include the Internet Protocol (IP).

The possibility also exists to design a T1 that can allocate one data channel of 512 kbps (or some other amount) to support Internet traffic and 18 channels of phone connectivity at 64 kbps.

In support of real time traffic, a channelized T1 could support 24 concurrent users transmitting 8 bits of information at a rate of 8000 transmissions per second. With additional front end equipment to multiplex user transmissions, it would be possible to allow more users to access the channels. The channelized T1 provides a guaranteed slot for the user's information. The channelized T1 also is sending frames at a fixed, predictable rate, with predictable amounts of delay.

Access to a channel guarantees a user a transmission slot as long as the call is set up. In a typical phone service scenario, access to the channel is on a first-come-first serve basis.

The limitation of the channelized T1 in support of real time traffic is the relatively small, fixed, 8 bit channels. If all of the information being transmitted will fit into the 8 bit channel, then it would be possible to utilize a channelized T1. If the data to be transmitted is larger than 8 bits, multiple consecutive channels would have to be used. With additional front end equipment, this would be possible. Higher transmission rate “Ts” are also available.

A better scenario is to have a larger channel available for the transmission of data.

A general limitation of the T1 is that if there are no data to transmit the assigned slot, the slot is transmitted empty. In addition, users only are able to transmit once per frame. It also does not support channel reallocation.

The positive aspects of a channelized T1 in support of real-time traffic are the dedicated channel to guarantee the user the required bandwidth, and that the T is a connection-oriented service.

## 1.4 RELATED WORK

The communication link that will be proposed in support of Synchronous Dependent data transmission can be viewed as a combination as a variable-size T-channel that allows channel reallocation and use of consecutive channels by the same user. The link can also be viewed as an Asynchronous Transfer Mode link that supports resource reservation and channel resizing.

In support of Synchronous Dependent transmissions, the T was designed to transmit voice in real time. A channelized T-1 was used to support the transmission of digital images[19], with the goal to determine the maximum number of users to be supported. The real time aspect of this study was to try and receive a user request prior to doing an auto-refresh at an enhanced resolution. The study did determine a maximum number of users that a T-1 could support in this form of real time application.

A similar type of communication link is a slotted ring. An ATM slotted ring is studied[20] in (20). The slotted ring in this case has frames that are alternately used for synchronous and asynchronous data transmissions. Frame sizes are dependent on the data rate of the ring. The access algorithm (Fair and Efficient Cyclic Control Algorithm, FECCA) in this case allows each node to determine the amount of synchronous data that will be transmitted. The algorithm[21] also used the reverse ring to transmit control information. It does not however, make use of the user characteristics to assist in the placement of the data in the frames, as proposed in the SD communication link of this dissertation.

The timed-token protocol[22] (TTP) is used as the media access method for the token bus, FDDI, and Safenet. As discussed previously, the TTP requires the network designer to carefully choose several network parameters.

Much research has been done regarding the admission control and scheduling algorithms in ATM networks[23, 24, 25, 26]. The research is designed to improve the capabilities of ATM to meet the timing needs for use with time-sensitive data by applying different schemes (round-robin, weighted round-robin) to the schedulers and calculations of worst case delays. If it were possible to pre-schedule when the data will be sent and minimize delay by assigning a channel to the user for data transmission, it is possible to improve upon the performance of the ATM systems.

The proposed work will provide a methodology to admit users with varying characteristics into single data stream, as opposed to the work of Maina[27], which places data of similar format into multiple CDMA data streams. The goal of Maina is to produce more information in a TDMA link by the CDMA encoding which can be effective in wireless networks where the level of power provides another dimension of encoding. If such an encoding is possible through power or frequency, the work of Maina can be used to allow multiple users in a single TDMA channel.

## 1.5 PROPOSED WORK

The transmission of time sensitive data across a communication link requires that the communication link have the capability of reserving resources and limiting delay and jitter. In addition, maximizing the usage of the link makes the link cost effective. The transmission characteristics of the users will affect the link, as well as congestion from other users and users that are transmitting too much information. Characterizing the users will determine which interactions among users will maximize the usage of the link.

For the class of systems with the requirement that sampled data and response signals reach their destination over a communication link within predetermined limits for delay, jitter, and timing, there are three factors that must be considered: the transmission link, the users, both synchronous and non-synchronous, and the admission control policy that will determine whether a user is granted admission to the link. It is the interaction of all three factors that will enable the proposed environment to support Synchronous Dependent transmissions.

The proposed research will develop the mathematical representation for a highly synchronous communication link. The representation will allow a data size characterization of a fixed width where the width can be recast to dynamically accept users without any deterioration of the existing user environment while maintaining an accurate repetition at proper time intervals.

Once the characterization of the transmission environment is finalized, the formulation will be expanded to describe a set of users {**U**} that can request admission to the transmission environment ***E***. The initial class of users of ***E*** will be assumed to have Synchronous Dependent (SD) requirements or to be capable of being characterized as such.

A mathematical model of the users will also be developed based on the fixed delay, zero jitter paradigms, i.e., capable of supporting *highly synchronous dependent* (SD) *data*.

Once the mathematical representation is developed for SD users, the conditions on admission will be analyzed to allow a characterization of a non-synchronous user, i.e., no fixed delay and no zero jitter requirements for a potentially large class of potential users that may not be SD. The representation for non-SD will be defined in terms of the SD users which potentially represent a relaxation in the SD user type to accommodate such traffic.

Given the current state of the transmission environment, ***E***, the next step will be to determine the functional mechanisms by which the users can be evaluated to determine if they can be admitted to ***E*** without disturbing the existing set of users, **{U}**, i.e., without disturbing the current state of ***E***.

With the given mathematical basis, the next step will be to determine that the result of admitting a known (or assumed) characteristics of the potential set of link users that will maximize the efficiency of the environment to service a class or classes of users. In the summation shown below, $\Phi$ is the number of frames per second and $\beta$ is the number of bits per frame. The product of $\Phi$ and $\beta$ is the maximum bandwidth available on the link. The term $\alpha$ represents the amount of bandwidth required for one sample by user $i$ and $\rho$ is the transmission rate of user $i$. The sum of all users from $n=0$ to $i$ is the total bandwidth required for all users over a known time $t$.

$$\sum_{n=0}^{n=i} \alpha_i \rho_i$$

The efficiency of the method developed in this dissertation is then:

$$(100 * \{(\sum_{n=0}^{n=i} \alpha_i \rho_i) / (\Phi * \beta)\})$$

In order to adequately address the admission alternatives, the admission parameters will include the possibility of limited time horizons. The non-SD users that join the system are assumed to be joining for a time that is significantly less than the SD users, due primarily to the non-periodic nature of their data transmission. The SD users are assumed to be similar to dedicated enterprise networks. In this sense, the time horizon for SD users is infinite for all practical purposes when compared to classical message/frame users. Thus, the non-SD users can be viewed as transients in the transmission environment ***E***. This addition of a contract time for non-SD users will provide flexibility in the method of analysis for optimization purposes.

In summary, the SD formulation of this dissertation allows for the coexistence of an enterprise network and a commercial data network.

To this point, the link is assumed to be simplex. The next step will be to analyze the characterization on ***E*** to incorporate the concepts of half duplex and full duplex communications. In reality, it will be more appropriate to consider two independent simplex links to achieve a full duplex link. However, the research will address this specific aspect of the problem.

As an example of the research and the link formulation, the operation of the link will be described in terms of one side of an existing T1 full-duplex transmission link. Because the SD environment is similar in structure to the T link, SD will be explained in these terms. This step will allow persons to quickly understand the research and formulation using a classic transmission link concept.

To demonstrate the class of problems for which this type of a link is important and a classic example problem will be chosen.

Finally, the environment ***E***, with both SD and non-SD users, will be contrasted with an existing communication concept/link such as ATM. This section will compare how ATM and SD systems handle users with SD-type requirements and users with non-SD-type requirements.

## 1.6 ORGANIZATION OF DISSERTATION

Chapter 2 will provide the characterization and model for the communication link and Chapter 3 will discuss the characterization and modeling of the users, as well as reviewing the effects of new users being granted access to the link and the effect of this on the other users. Chapter 4 is a discussion of the methodology of evaluating the admission of the specific user that will evaluate the specific user's request to enter the link and the resources available to the user.

Chapter 5 is a discussion of the need to provide full-duplex communication for the SD link. Chapter 6 compares the SD link to the operation of a T-1 and to the operation of ATM. Chapter 7 is an examination of a classical real-time problem and the utilization of the SD link to serve as the communication link. Chapter 8 provides the conclusion, the contribution, and suggestions for future research.

# 2.0 THE COMMUNICATION LINK

Most early communication services began with the intent to provide support for only one primary purpose. Ethernet was designed for the purpose of interconnecting workstations, servers, and printers[28] to support data transmissions that were not time-sensitive. The analog telephone and later the digital T's were designed to provide voice services. The cable television system originally supported service to supplant broadcast television.

In recent years, with increased speed and improved communication services, there has been a convergence of services, or classes, in all three of the communication domains. In some cases, modifications have been made to handle real time transmissions (Ethernet, IP, and MPLS). In other cases, support for all three applications (voice, data, video) was considered in the design (ATM). Voice, data, and video all have specific requirements related to their transmission of information.

To support multiple classes of traffic, the communication link proposed in this dissertation will provide support for the class of traffic with the most stringent requirements, those users with real time constraints, and then provide support for other classes as is possible.

The data transmitted across the network communication link that supports a distributed system is highly synchronous in that samples are sent at fixed periodic intervals. While the term "synchronous" has different connotations in relation to computer data transmissions, in this context synchronous refers to the periodic transmission of a real-time data, as well as the isochronous traffic of a digital TDM system. This type of traffic will be referred to as highly Synchronous Dependent (SD).

The previous chapter provided a brief description of various network communication services and their characteristics. The services in the previous chapter were not meant to be all-inclusive, but rather indicative of the characteristics of communication systems and some methodologies to support distributed SD traffic.

Shown in Table 2.1 is a summary of some of the characteristics of network communication services. There are several characteristics of networks that provide more support for Synchronous Dependent traffic that are incorporated in the proposed communication link.

Inherent in all communications is the potential for delay. Fixed or predictable delay can be accounted for. Variable delay affects the guaranteed delivery of data. Connection-oriented services such as ATM, Frame Relay, and T-channels do not have the variable delays associated with the routing required with non-connection-oriented networks. The delay is the amount of time required for the packet containing the message to traverse the communication link from source to destination[29]. Delay can also be affected by network congestion from allowing too many users access to the network, or perhaps just one user that is transmitting too much information too quickly. Delay can be detrimental to the support of SD traffic, since there may be a fixed deadline associated with a particular data transmission. The delay associated with network congestion can be eliminated by resource reservation.

Fixed packet length services such as ATM and T-channel allow for more predictable delay as compared to variable packet length services. Variation in delay is referred to as jitter. Jitter can be caused by variations in packet size that may cause the next packet to be sent either too early or too late.

**Table 2.1. Network Communication Characteristics**

| **Network Communication Service Characteristics** | |
|---|---|
| Broadcast | Simple way for a host to reach all of its neighbors |
| End-to-End | A connection across a set of interconnected domains |
| Link Capacity | The maximum number of … bits that can be transmitted from the source and correctly received by the destination for some time interval ***t*** to time ***t+I***[30]**,** divided by ***I*** |
| Resource Reservation | The capability to request specific qualities of service from the network for particular application data streams or flows |
| Delay | The amount of time required for the packet containing the sampled data to traverse the communication link from source to destination |
| Message Path | The geographical path that is followed by a call or message over the circuits that are used in establishing a chain of connections[31] |
| Message Size | The size of the packet or frame containing the data |
| Jitter | The difference between the delays of two packets that traverse the communication link from source to destination[32] |
| Critical Importance | The degree to which the failure to deliver the message will result in a catastrophe |
| Admission Control | The set of actions taken by the network during the call set-up phase (or during call re-negotiation phase) in order to determine whether a connection request can be accepted or should be rejected (or whether a request for re-allocation can be accommodated)[33] |
| Media Access Control | The media access control sub-layer is the portion of the 802 standard that mediates and controls access to the ring (media)[34] |
| Synchronization | The coordination of a sending and receiving device, so that both simultaneously send and receive data at the same rate.[35] |
| Guaranteed Transmission Slots | Users have a dedicated time slot for the transmission of information[36] |
| Number of Users | Two types of users; those that have access to the communication link and those that use the link |
| Addressing | Method to identify the destination of a transmission |

Jitter can also be caused by variation in the route taken by successive packets across a network. Predictable delay can be acceptable to an SD network, but variation in delay cannot.

The media access method refers to how users are granted permission to transfer data. A contention-based service such as Ethernet does not provide sufficient guarantees of access to the communication link to support real-time traffic. Services such as ATM that provide for resource reservation or a service that uses the timed token protocol and provides predictable transmission times are more suited towards the transmission of SD traffic. However, even these systems do not provide a guaranteed slot for the transmission of SD data.

The terms broadcast and end-to-end are meant to show two ends of a spectrum, where broadcast is used for a message sent to multiple users, and end-to-end implies a communication between a sender and receiver, with the end-to-end communication possibly occurring across multiple networks. Message path can indicate the path of the end-to-end communication.
A communication system that provides end-to-end service maintains a path from source to destination each user. End-to-end service is provided in a phone call over land lines. ATM sets up a virtual path for users.

The terms resource reservation and guaranteed transmission slot are indicative of two methods of providing resources to a user. Resource reservation may imply that a certain amount of bandwidth has been requested and reserved, while a guaranteed transmission slot indicates a slot reserved for a particular user. ATM and Differentiated Service provide resource reservation and a "T" would provide a dedicated channel.

To provide support for an SD communication link, the link should be connection-oriented, allow for resource reservation, have a methodology to admit certain users, provide fixed delay and zero jitter services as needed, and have a fixed packet length. The next section will discuss the proposed communication link and its characteristics in support of SD traffic.

## 2.1 THE LINK CHARACTERISTICS

Shown below is a summary of network communication service characteristics from the previous section:

- Broadcast
- End-to-End
- Link Capacity
- Resource Reservation
- Delay
- Message Path
- Message Size
- Jitter
- Critical Importance
- Admission Control
- Media Access Control
- Synchronization
- Guaranteed Transmission Slot
- Number of Users
- Addressing

In relation to the characteristics shown above and in support of Synchronous Dependent data transmissions, the proposed communication link and method of determining the result of the user admission can be summarized as:

> "A link that provides a resource reservation in the form of a guaranteed time slot(s) of fixed size, that can be reset as needed. The link is part of a communication system that is connection-oriented, in that there exist a path from source to destination. The synchronization of data to other parts of a distributed system is provided by a real time clock. The admission determination will provide the amount of bandwidth required, which may be in the form of so many bits with a known periodicity, as well as limits on jitter and delay. In the case of multiple links connected through an interface device, the path will be known in advance. The admission analysis will

determine whether the user requesting admission will interfere with the transmission of other previously admitted users and determine whether the new user should be admitted to the link."

The proposed communication link will reserve a channel for each user that requires the transmission of information at a fixed time. The link will have channels similar to a T-1 channel. This type of communication link was specifically chosen to support the SD users transmitting at periodic rates.

While the typical frame length of a T-1 is 24 channels, there will be no initial fixed frame length of the SD link. The channel size of a T-1 is a fixed 8 bits in length. The channel size of the SD link will be adjustable, dependent on the requirements of the users in the system. It can be set at a particular size at the outset, and then modified to accommodate the users utilizing the link. However, all channels when modified will be the same size.

The communication link will be able to provide two or more consecutive channels for a user that is admitted, something that cannot be done in the standard T-1 link.

The channel reserved for a user of the T-1 link cannot be used by another user, because all 24 users are transmitting at the fixed rate of 8000 times per second. If there are only 23 users utilizing the T-1, the 24th channel will remain empty. With the SD link methodology, two users transmitting at rates of 4000 times a second could transmit in the same channel in alternating frames.

The SD link will also have to provide service to users that have lesser requirements than the real-time users. This would include but not be limited to users transmitting email messages and similar applications. Channels allocated for the non-Synchronous Dependent (non-SD) users will also be reserved.

It is assumed that the users transmitting SD data will be transmitting at a fixed, periodic rate. There will then be a channel reserved for the hard real-time user for every instance of transmission. If the communication link provides the reserved channel, jitter and delay should not affect the SD user[37].

It will be shown that jitter and delay are introduced by users that are transmitting at a rate that is not compatible with the existing users already admitted to the link. Consider the standard T-1 link as an example. The T-1 frame is comprised of 24 channels transmitting at a rate of once every 125 microseconds. The hypothetical user transmitting at a rate of once every 120 microseconds requesting admission to the T link will impact the other users of the link, if the user is granted admission to the link.

Because of the severity of the consequences associated with the failure of the control mechanism for an SD system, the communications link of the control system must provide guarantees to the users, relative to the amount of delay, jitter, and loss that will occur as the information traverses the network.

The amount of delay, jitter, and loss that occur in a system determines the Quality of Service (QoS) that can be offered to a user of the system.

The proposed communication link is a channel-based layer 2 link. Unlike the T-1, which has 24 channels which comprise a frame, the proposed communication link (now to be referred to as the SD link) does not have a pre-determined frame size. The exact nature of the frame sizing will be discussed in the next section.

Similar to the T-1, the channel that is allocated to the user will indicate the source and destination of the information in the channel.

Shown in Table 2.2 is a summary of the characteristics of the T-1, and ATM link, and the communication link ***E***.

**Table 2.2. T, ATM, and Link E Characteristics**

| **Characteristic** | **T-1** | **ATM** | **Link *E*** |
|---|---|---|---|
| Variable Channel (Cell) Size | No | No | Yes |
| Resource Reservation | Yes | Yes | Yes |
| Connection Oriented | Yes | Yes | Yes |
| Dedicated Channel | Yes | No | Yes |
| Consecutive Channel Cell Use for the same user | No | Yes | Yes |

The communication link of the Synchronous Dependent (SD) environment ***E*** has a maximum link capacity $\boldsymbol{\Gamma}$ and a periodic channel rate of $\boldsymbol{\Phi}$ channels per unit time. The channels are of equal size and have a data capacity of $\boldsymbol{\beta}$ bits per channel. The channel size ($\boldsymbol{\beta}$ bits per channel.) can be adjusted on a per link basis to better accommodate the users of the link. The relationship between $\boldsymbol{\Gamma}$, $\boldsymbol{\Phi}$, $\boldsymbol{\beta}$ is

$$\boldsymbol{\Gamma} \text{ bits/unit time} = \boldsymbol{\Phi} \text{ channel/unit time} * \boldsymbol{\beta} \text{ bits/channel} \qquad \textbf{(1)}$$

Admission to the link will be granted or denied by the result of the method of analysis made possible by this formulation of the problem, which is discussed in chapter 4. Admission to the SD network is based on the ability of the network to support the user's needs as related to amount of data to be transmitted, how frequently the data must be transmitted (periodicity), and the user's requirements for limits on delay, jitter, and timing.

## 2.2 THE LINK MODEL

Prior to any user being granted access, the communication link is a continuous set of bits with no pre-determined channel size and no pre-determined set of frames or frame length that would indicate the period or repeatability of the channels. The bit is the lowest level of information to be transmitted across the communication link. In the context of the T-1, bits are the lowest level of information transmitted across the T-1.

The T-1 is comprised of 8 bits of data per channel. The channel is the second lowest level of information in the T-1. The communication link ***E*** does not have a fixed channel size. The channel size will be determined by the requirements of the users

In the context of the T-1, 24 channels make up a frame. The beginning of the frame is indicative of the beginning of the next set of transmissions by the users who have been granted access to the link. It is anticipated that the frame will have similar significance in relation to the communication link ***E***. The number of channels in a frame in the link ***E*** will be determined by the first user to be granted access to the link. Given the highly periodic nature of the SD traffic, the repetition of transmitted data will occur similar to the T-1. It just may not occur at the same rate for all users, and it can be interspersed with non-periodic data. In the context of the communication link ***E***, the frame is defined in a manner that can be described as the opposite of the T-1 link. In the T the frame (and the sync bit) indicates the repetition of user data; in the communication link ***E***, the repetition of a particular set of user data (the fundamental user) will mark the start of a new frame.

Shown in Figure 2.1 is a representation of the communication link prior to any user being admitted.

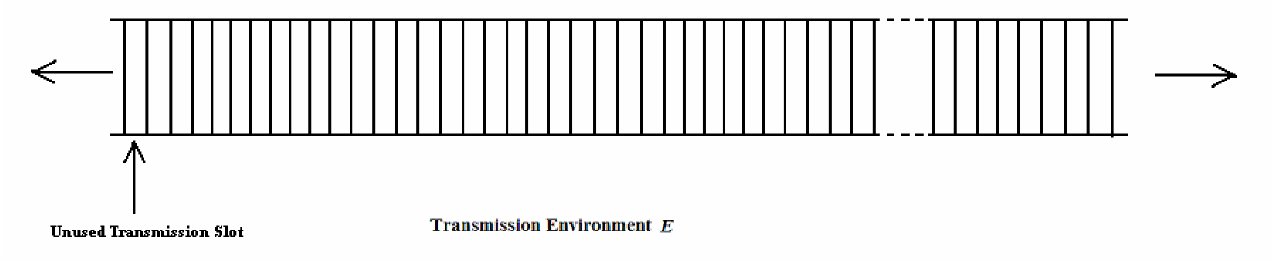


**Figure 2.1. Transmission Environment *E***

The representation in Figure 2.1 shows the link ***E*** as a continuous set of unused transmission slots. The transmission slot is available for one bit of data. At this level, one bit of data could constitute a channel. Without any users, there are no channels defined and there are no frames defined.

To build the model of the communication link that includes bits, channels, and frames, and without loss of generality, set one second as the value for unit time. Prior to any user being admitted to the link, the link itself is synchronous in nature in that a transmission slot (occupied or not) is sent every $1/\Gamma$ seconds. If one bit is a channel, $\Gamma = \Phi$, the link rate per unit time is equal to the channel rate per unit time. Although there is no pre-defined channel or frame to model the link, the unit time can be used as the frame length to develop the model. A frame can then initially be defined as consisting of $\Phi$ channels. The transmission of each channel will be synchronized with a real time clock.

Taking advantage of the periodic nature of the communication link, a sine wave can be used to model a frame on the link ***E***.

However, it is not the entire sine wave that is necessary to model a frame on the link. Only the zero-crossing of the sine wave is needed to indicate the start of a new frame that is $\Phi$ channels long.  This is shown in Figure 2.2, where the sine wave intersects the channel that is the first channel in the frame.

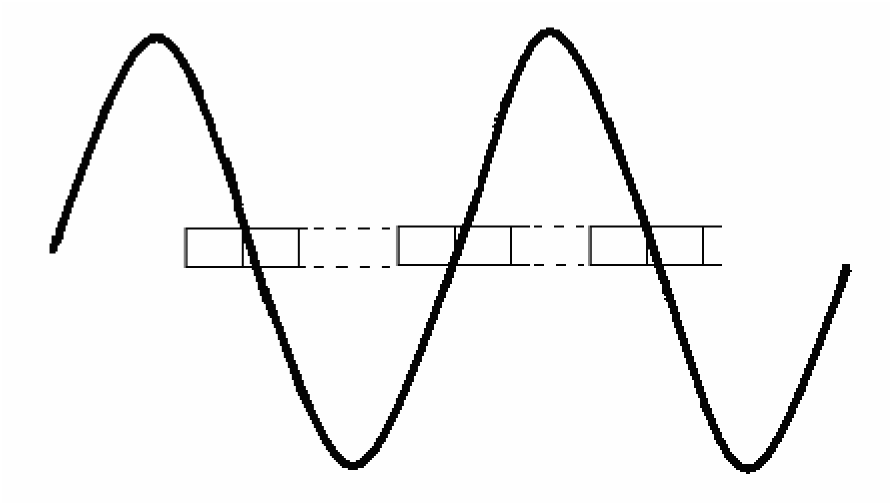


Figure 2.2. Sine Wave Marking a Frame Start

A symbol to represent the zero-crossing is shown below

┼

and the equation for the beginning of each frame in ***E*** is

$$f(E_f) = ┼ \sin(\omega t) \qquad \text{for} \quad 0 \leq \omega t < 2\pi \tag{2}$$

where the frequency ***ωt*** indicates the frequency at which each frame is started.

However, there will be two zero-crossings per $2\pi$ period relative to the characteristic equation. Each zero-crossing represents the start of a frame, i.e., there are two frames per $2\pi$ period.

To represent more accurately the fact that the second frame in the period $0$ to $2\pi$ is a new frame a better representation of the function $f(E_f)$ would be:

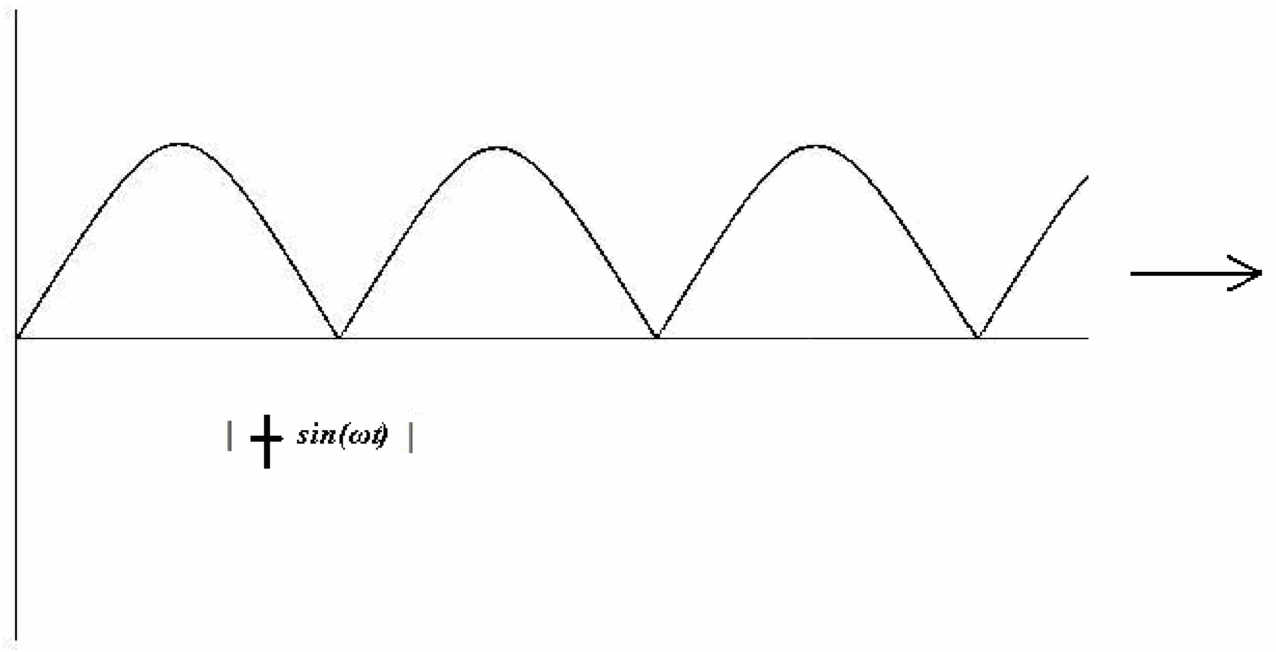


**Figure 2.3. The absolute value of the characteristic equation of $E_f$**

where the wave appears as a rectified or absolute value of the original sine wave such that:

$$f(E_f) = + | \sin(\omega t) | \qquad \textbf{for} \quad 0 \leq \omega t < 2\pi$$

This alternative notation is introduced to indicate the basis on which calculations can be made as opposed to a cycle of the sine wave which repeats every two frames.

The representation of $f(E_f)$ is valid with or without the absolute value sign. The absolute value is used to demonstrate that there are two transmissions (zero-crossings) over the $2\pi$ period.

Using a time-based definition of the frame is one method to characterize the link ***E***. The primary purpose of the communication link ***E***, though, is to support the periodic transmissions of users with Synchronous Dependent data transmissions. To make use of this, the first user to be granted access to the link will be required to be an SD user, or is a user that can be characterized as an SD user. The first SD user will place data in the continuous, unformatted link in a manner similar to the figure shown in Figure 2.4. The size of the channel will be determined based on the amount of data being transmitted by the user. However, the channel size can be larger, equal to, or smaller than the data per transmission of the user.

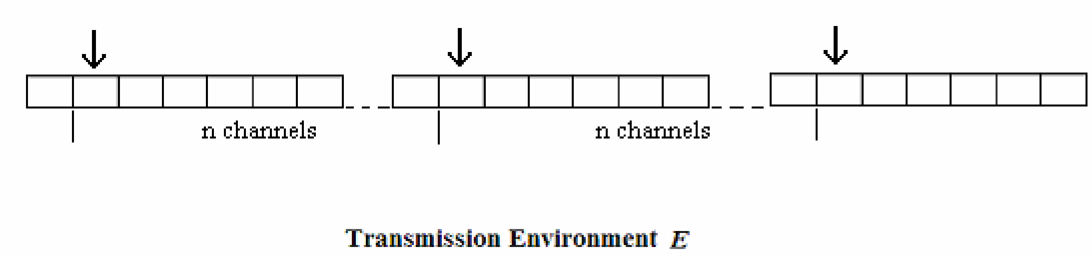


**Figure 2.4. Transmission Environment *E***

In the figure above there are ***n*** channels between each transmission by the first SD user, **User A**, granted access to the link, inclusive of the first channel used for transmission by the user. An assumption is made here, without loss of generality, that ***n*** is a multiple of the channel rate ***Φ*** such that

$$n * m = \Phi \qquad n, m, \Phi \in I+, n < \Phi \qquad (3)$$

In the example above, ***m*** is the number of transmissions by user ***A*** per unit time and ***Φ*** is the total number of channels per unit time. The case where ***m*** is not an integer in equation **(3)** will be explored in "The User" chapter.

The transmission of data by the SD user can again be represented by the previously discussed sine wave. The transmissions of the SD user can then be modeled by:

$$\boldsymbol{f(E_A) = + \sin(\omega_A t)} \qquad \textbf{for} \quad \boldsymbol{0 \leq \omega t < 2\pi} \qquad \textbf{(4)}$$

where $\boldsymbol{f(E_f)}$ is equal to $\boldsymbol{f(E_A)}$ and $\boldsymbol{\omega_A t}$ is the transmission frequency of the User A.

Between each transmission of the SD user that is used as the frame delineator is a set of ***n*** channels. Each channel from ***1*** to ***n – 1*** can likewise be represented by a series of sine waves as shown in Figure 2.5.

The characteristic equation for the set of sine waves used to model the communication link ***E*** with **User A** defining the frame length is then

$$f(E) = + \sum_{j=0}^{n-1} \sin(\omega_j * t) \qquad \textbf{(5)}$$

The limits from ***0*** to ***n – 1*** indicate the number of sine waves that will be needed to represent the channels in ***E*** up to the point where the first sine wave begins to repeat. Once again, the point where the sine function is equal to zero indicates the start of a channel.

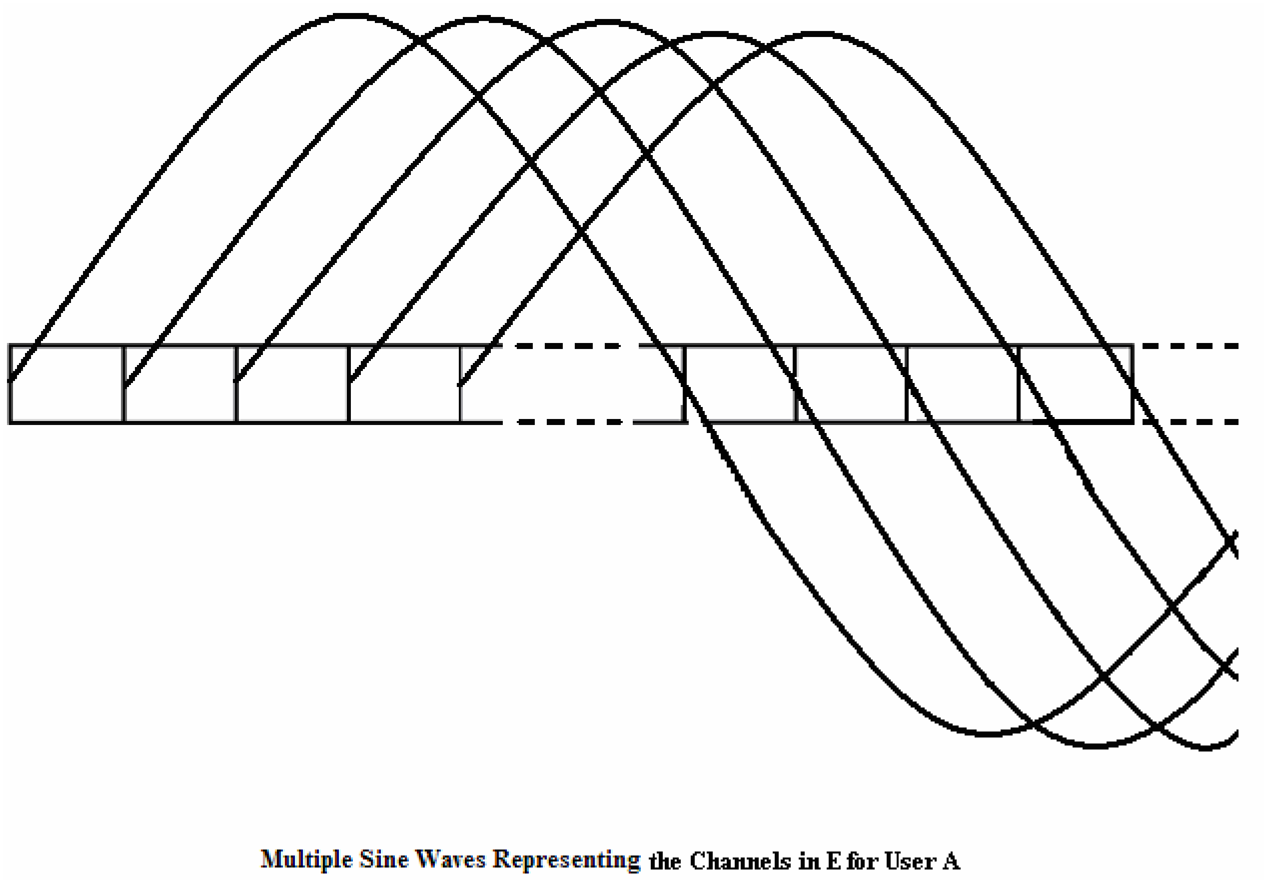


**Figure 2.5. Multiple Sine Waves Representing the Channels in E for User A**

An alternate model for ***E*** is to allow each channel ***1*** through ***n - 1*** to be represented by a phase shift relative to the original sine wave used to model the first SD user to be granted access. The characteristic equation of this model would be

$$f(E) = + \sum_{j=0}^{n-1} \sin(\omega * t + \varphi_j) \qquad \textbf{(5)}$$

Because there are two zero-crossings per $\boldsymbol{2\pi}$ period and therefore two transmissions by a user over the same period, the period $\boldsymbol{\varphi_j}$ is from $\boldsymbol{0}$ to $\boldsymbol{\pi}$ such that

$$f(E) = + \sum_{j=0}^{n-1} \sin(\omega * t + \varphi_j) \qquad \text{for } 0 \le \omega t < 2\pi \qquad (6)$$

$$\text{and } 0 \le \varphi_j < \pi$$

## 2.3 ALTERING THE CHANNEL SIZE

The communication link $E$ has a maximum link capacity of $\Gamma$ bits per unit time with $\Phi$ channels per unit time and $\beta$ bits per channel such that

$$\Gamma \text{ bits/unit time} = \Phi \text{ channel/unit time} * \beta \text{ bits/channel}$$

While $\Gamma$ is fixed, $\beta$ is configurable, which changes $\Phi$. Depending upon the environment in which the link is being used, a particular size of channel may be more advantageous. The purpose of the configurable channel size is to allow for an optimization based on the amount of data being transmitted by the SD users.

There are several factors that can be considered when determining the size of the channel.

The first is the amount of data being transmitted by the user(s). One of the measures of link efficiency is when there is 100 % link utilization. This can be interpreted in different ways.

If all the channels in the link are carrying data, then it can be said the link is 100 % efficient. However, if each channel has a capacity of $\beta$ bits and the channels are carrying $\beta/10$ bits, is there 100 % efficiency?

If, as part of the Connection Admission Control criterion, the anticipated bits per channel are part of the SD user's setup information, it may be possible to optimize the size of the channel.

The purpose would be to either fill the channels to capacity and/or increase the number of channels that are available to all users.

The balancing act will occur relative to the non-SD users, who may be transmitting relatively large files as compared to the SD users. For a large file, the more channels that are required to transmit the information, the less efficient the transmission operation becomes.

Consider that the size of the channel for the T-1 is 8 bits and the ATM cell size is 53 bytes, both of which are fixed. Then consider the size of the Ethernet frame has maximum size of 1500 bytes and that Token Ring can have frames as large as 5000 bytes. The fixed sized services provide greater predictability; the variable size services have lower overhead, although arguably T-1 has no overhead, just a low data rate.

The communication link ***E*** will attempt to take advantage of the fixed channel size predictability while also utilizing the capability to vary channel size as needed to serve the needs of the users.

# 3.0 THE USERS

There are two general types of users that will request access to the communication link: those that have Synchronous Dependent (SD) requirements and those that have non-Synchronous Dependent (non-SD) requirements. SD users will transmit information at a periodic (synchronous) rate; non-SD users will transmit information aperiodically. SD users will typically have requirements for jitter, delay, and required bandwidth, as well potentially a requirement for a fixed time when transmissions must occur and be received. Non-SD users will not have requirements for delay and jitter.

## 3.1 USER CHARACTERISTICS

There are subclasses to the users classes (SD and non-SD) already discussed. The sub-classes are summarized below:

1.) An SD user that has the same transmission rate $\boldsymbol{\omega_i}$ as the first user.
2.) An SD user that has a transmission rate $\boldsymbol{\omega_i}$ that is greater than the first user's transmission rate.
3.) An SD user that has a transmission rate $\boldsymbol{\omega_i}$ that is less than the first user's transmission rate.
4.) An SD user that has a finite amount of SD data to transmit. So far, it has been assumed that an SD user is continuous, i.e., it has an infinite horizon in its transmission. This may not be the case for some users. A user with a finite amount of SD data to transmit

may request access to the communication link. In the case of finite SD data streams, these will be considered as similar to non-SD data streams.

5.) A user (SD or non-SD (continuous or finite)) that requires more than a single frame for the transmission of its data.
6.) Users with jitter requirements.
7.) Users with delay requirements.
8.) Users with synchronous time requirements.
9.) Users that are not integer multiples of the first (fundamental) user.

A summary of all User Classes is shown in Table 3.1.

**Table 3.1. User Classes and Characteristics for the Communication Link *E***

| | | User Characteristic | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SD | Multiplier of Fund. User | Not a Multiplier of Fund. User (Not Including Prime) | Jitter Allowed | Delay Allowed | Infinite Transmission | Finite Transmission | Aperiodic (non-SD) |
| | 1 | X | X | | | | X | | |
| User Class | 2 | X | X | | X | | X | | |
| | 3 | X | X | | | X | X | | |
| | 4 | X | X | | X | X | X | | |
| | 5 | X | X | | | | | X | |
| | 6 | X | X | | X | | | X | |
| | 7 | X | X | | | X | | X | |
| | 8 | X | X | | X | X | | X | |
| | 9 | X | | X | | | X | | |
| | 10 | X | | X | X | | X | | |
| | 11 | X | | X | | X | X | | |
| | 12 | X | | X | X | X | X | | |
| | 13 | X | | X | | | | X | |
| | 14 | X | | X | X | | | X | |
| | 15 | X | | X | | X | | X | |
| | 16 | X | | X | X | X | | X | |
| | 17 | | | | | | | | X |

## 3.2 THE USER MODEL

Each user ***i***, both SD and non-SD, requesting admission to the communication link ***E*** will be modeled by using a form of the general equation used to represent the individual channel of the communication link, shown below.

$$f(E) = + \sum_{j=0}^{n-1} \sin(\omega * t + \varphi_{j})$$

The equation for **User *i*** will have a transmission frequency $\boldsymbol{\omega_i t}$ and a phase shift $\boldsymbol{\varphi_i}$ relative to the start of the frame.

$$\boldsymbol{f(E_i) = + \sin(\omega_i t + \varphi_i)} \qquad \textbf{for} \quad \boldsymbol{0 \le \omega_i t < 2\pi} \qquad \textbf{(7)}$$

$$\textbf{and} \quad \boldsymbol{0 \le \varphi_i < \pi}$$

The $\boldsymbol{\omega_i}$ term is the angular frequency and when divided by $\boldsymbol{2\pi}$ represents the linear frequency of the user and how frequently the user will transmit information across the link ***E.*** Although the function $\boldsymbol{f(E_i)}$ is periodic over $\boldsymbol{2\pi}$, the phase shift will be periodic over $\boldsymbol{\pi}$ since there will be two zero-crossings per $\boldsymbol{2\pi}$ period of the sine function (see Section 2.2). The phase shift will be relative to the first user approved for entry to the communication link by the method of analyzing the effect of admitting this first user.

The characterization of each user granted admission to the communication link requires that the starting point of each channel assigned to the user correspond to a zero crossing of the user's characteristic sine wave. Each zero-crossing is representative of a specific time slot (channel) that is reserved for a user, with the guarantee that at the next zero-crossing of the characteristic equation the slot will be available again, reserved for the same user. As will be discussed later, even though the slot is reserved for a user, the channel could be in use by another user. The availability of a slot must be observable as related to the analysis of the result of potential admission.

## 3.3 THE FUNDAMENTAL USER

The first user to be granted admission to the communication link is a Synchronous Dependent (SD) user, or a non-SD user that can be mapped to the characteristic representation and appears as SD. Logically, the first user will have the same number of channels between transmissions, making it appear the same as an SD user. This is by design. Because the communication link is designed for users with SD requirements, it is reasonable to assume that the fundamental user would appear to be SD compliant.

The placement of **User A's** data into a specific channel in ***E*** is based on having a zero jitter and a fixed delay requirement, i.e., the data is placed in the frame that is precisely specified by the user's requirements. This is a logical placement. Since the fundamental user's transmissions are used as the frame delimiter, the fundamental user's channels are logically marked. However, it is possible that the fundamental user could allow some jitter and/or delay, and the actual data may reside in another location which is the physical placement of the data. Placement with jitter and delay are considered further in this section.

The frequency of transmission of the first user has an impact on the other users that will eventually request access to the communication link. This will be discussed in the next section.

The first user, **User A**, to be granted access to the communication link ***E*** will be designated the ***fundamental user*** and is represented by the notation:

$$f(E_A) = \pm\sin(\omega_A t + \varphi_A) \qquad \text{for} \quad 0 \leq \omega_A t < 2\pi \qquad (7)$$

$$\text{for} \quad 0 \leq \varphi_A < \pi$$

As more SD users are granted access to the communication link, the fundamental user will be the user that has the longest period between transmissions.

The fundamental user will have a zero phase shift and all users entering the link will have a phase shift relative to the fundamental user over a period of $\pi$. The $f(E_A)$ has two occurrences (zero-crossings) of transmissions for **User A** over the $2\pi$ period. This is summarized below:

> **Definition 1:** The first user to be granted access to the communication link will be designated the fundamental user. The user will have the characteristic notation
>
> $$f(E_A) = \pm\sin(\omega_A t + \varphi_A)$$
>
> with a phase shift of zero. All users entering the link after the fundamental will utilize the same characteristic notation but will have a different phase shift relative to the fundamental user.

The second occurrence of transmission for the fundamental user frequency will occur at

$$f(E_A) = \pm\sin(\omega_A t + \pi)$$

with the phase shift $\varphi_A$ in this case equal to $\pi$, indicating where the next transmission in the link will occur.

The transmissions of the fundamental user will define the frames on the communication link ***E***. The channel that contains the first transmission by **User A** will indicate the beginning of the first frame and the channel containing the second transmission by **User A** will indicate the beginning of the second frame in ***E***. The channel prior to the second transmission of **User A** and all channels immediately preceding the next set of transmissions of **User A** will signify the end of the previous frame. In contrast to the fixed frame length of the T-1, the frame length of the communication link E is determined by the frequency of transmission of the fundamental user.

**Definition 2**: A channel is defined as the unit of data transfer. All channels in a link will be of the same length. The length of all the channels can be modified and will be initially determined when the first user requests access. The length can also be modified after users have been granted access to the link.

**Definition 3**: A frame is defined as the number of channels between transmissions of the ***fundamental user***, inclusive of the first channel used by the ***fundamental user***.

There are several initial conclusions that can be inferred regarding the characteristics of the fundamental user.

The first conclusion is that the transmission rate of **User A** per unit time cannot be faster than the available channel rate $\boldsymbol{\Phi}$ per unit time such that

$$\omega_A / 2\pi \leq \Phi \qquad (8)$$

Second, the data amount $\alpha_A$ of **User A** cannot be so large as to overfill an entire set of channels between the (*ith*) transmission and *(ith+1)* transmission of **User A**, relative to the frequency of transmission of **User A**. For example, if **User A** were transmitting at a rate that allowed one channel in between transmissions and the data from **User A** was such that it filled three channels, the link could not handle the transmissions.

Third, assume **User A** transmits its data at a rate of $\omega_A/2\pi$ per unit time such that $\omega_A/2\pi$ transmissions per unit time is a rate less than the rate of $\Phi$ channels per unit time. The data transmitted by user **A** has size $\alpha_A$ bits per transmission. The size of $\alpha_A$ can be greater than, less than, or equal to $\beta$ (the channel size in bits). If $\alpha_A$ is larger than $\beta$, user **A** will require more than one channel to transmit its data. The integer portion of the quantity (rounded up to the next integer)

$$\alpha_A / \beta$$

provides the number of channels per sample that **User A** requires to transmit its information. The quantity

$$\alpha_A \, \omega_A / (\beta \, 2\pi)$$

equates to the number of channels per unit time that **User A** requires to transmit its data. It is required that **User A** transmit its data in continuous channels (if more than one channel is required for **User A's** data), and one bit in a channel will constitute use of the entire channel. The quantity

$$\ulcorner(\alpha_A \, \omega_A) / (\beta \, 2\pi)\urcorner \text{ channels per unit time} \leq \Phi$$

is the same number of channels per unit time, with the “$\ulcorner x \urcorner$” operator indicating the quantity has been rounded up to the next integer.

The final conclusion that can be drawn regarding the **User A** is relative to the transmission rate of **User A**. Assume **User A** is an SD user or non-SD user that can be characterized by the characteristic notation. **User** A has a transmission rate of $\omega_A / 2\pi$ per unit time, which is less than $\Phi$. Define $y$ as equal to $\omega_A / 2\pi$. The value of $y$ must be some value such that

$$y * n \leq \Phi \qquad\qquad y, n, \Phi \in I+ \tag{9}$$

where $n$ is the maximum number of frames per unit time. The value y also indicates the number of frames in $\Phi$ per unit time.

Shown in Figure 3.1 is a representation of the communication link $E$ with the fundamental user, **User A**, having been granted access.

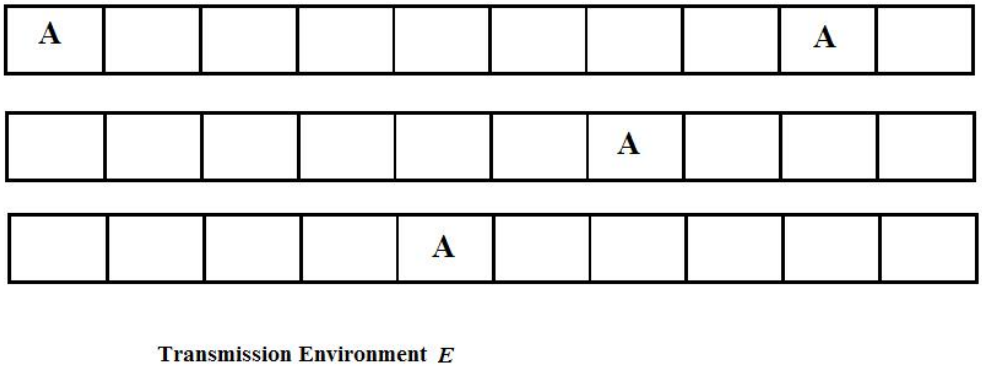


**Figure 3.1. The Fundamental User in *E***

Now that the fundamental user has been granted access to the communication link and a characteristic equation defined, what must be determined is:

a.) The maximum transmission frequency of the next user to request access to the communication link?

b.) Is there a minimum transmission frequency?

c.) What is the impact of users with the same transmission frequency as the fundamental user?

d.) In addition, the effects of jitter, delay, finite transmissions, and aperiodic (non-SD) traffic must also be considered.

These questions are answered in the following sections.

### 3.4 ADDITIONAL SD USERS TO THE COMMUNICATION LINK

The admission of the fundamental user, **User A**, to the communication link ***E*** and the creation of a series of frames based on the transmission frequency of **User A** will have an affect on the other users that will be requesting access to the link ***E***.

Using the notation from the previous section, there are ***y*** frames per unit time and ***n*** channels per frame. The equation for the ***ith*** frame in the communication link ***E*** for the case when all users are transmitting at the same rate as the fundamental user is shown below:

$$f(E_i) = \sum_{j=0}^{n-1} \left( + \ \sin(\omega_A * t + (j\pi)/n) \right) \qquad \textbf{for} \quad 0 \le \omega_A t < 2\pi \qquad \textbf{(10)}$$

Each channel in the ***ith*** frame is identified as a phase shift relative to the fundamental user in channel 0. The fundamental user has a phase shift of zero.

If **User A** is a zero jitter and fixed delay SD user, only users which will not interfere with the transmissions of **User A** can be admitted to the link ***E***. An example of the class of user that is compatible with **User A** is an SD user that occupies the same channel in each frame, i.e., that has the same phase shift relative to the fundamental user. This class of user would be similar to **User A**. Conversely, if **User A** is allowed to have some degree of delay and jitter, it can be shifted from its "designated channel" to allow users that are not similar to be admitted to the link. Delay and jitter are discussed in the next sections.

There is also a limitation to the frequency of transmission available to each subsequent user requesting admission to the ***E***. The limitation on the fundamental user was that the transmission rate could not be faster than the transmission rate of the link $\boldsymbol{\Phi}$. The limitation on the next SD user is dependent on the number of channels that are unoccupied in each frame, analogous to the limitation on the number of phone calls in a 24 channel T-1.

Relative to Table 3.1 on page 38, there are three possibilities that are part of the class of user "multipliers" for new SD users as they are admitted to the communication link:

1) An SD user transmitting at a rate that is the same as the fundamental user.
2) An SD user that is transmitting at a rate that is faster than the fundamental and that the fundamental is a multiplier.
3) An SD user that is transmitting at a rate that is slower than the fundamental and that is a multiplier of the fundamental.

These three possibilities will now be discussed.

### 3.4.1. User B has the same transmission frequency as User A

**User B** has requested admission to the communication link ***E*** after the fundamental **User A** had been previously admitted and **User B** has a transmission rate $\omega_B$ such that

$$\omega_B / 2\pi \leq \Phi$$

and

$$\omega_A = \omega_B$$

under the same condition as **User A,** i.e., the data from **User B** fits into a single frame.

An additional possible requirement for **User B** is that the **User B's** requirements cannot include having to have the transmission of its data require the use of the frame being used by **User A**, if both **User A** and **User B** are operating under a zero jitter requirement. One possible representation for **User B** joining **User A** in ***E*** is shown below.

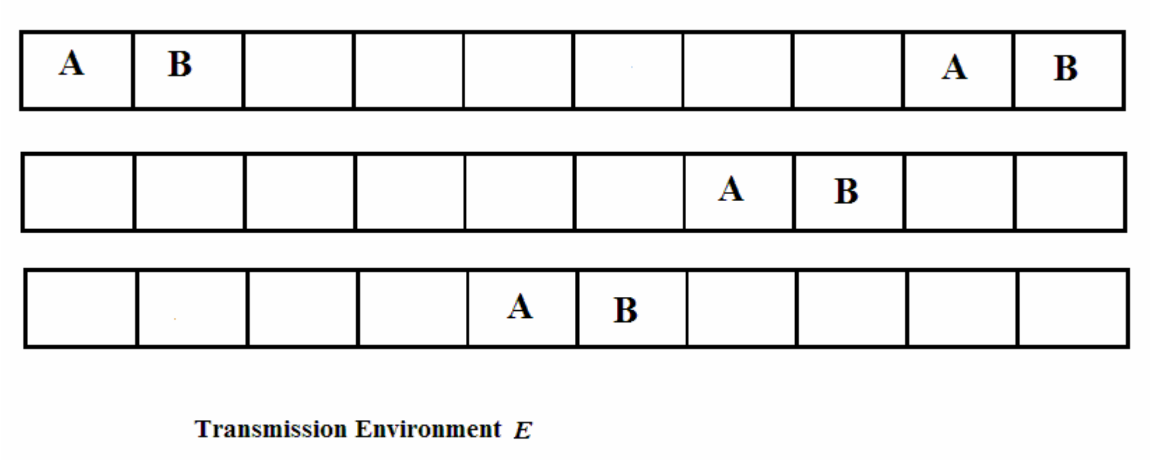


**Figure 3.2. User A and User B in the communication link *E***

Even though the frequency of transmission of the users is the same, **User B** will have an associated phase shift $\varphi_B$ which indicates the position of the data in the communication link $E$ relative to the **User A**.

To insure that **User B** (and **User A**) can both transmit at the required times and will not interfere with the transmissions of the other user, the two users must have independent zero crossings. To verify that they have independent zero crossings, consider proving the opposite, i.e., when will the two have the same zero crossing as represented by the phase shift. If the two users have the same phase shift, they would occupy the same channel in the link.

Let **User A** be characterized by $\sin(\omega_A t)$ with a phase shift of $0$ and **User B** be represented by $\sin(\omega_B t + \varphi_B)$.

$$\sin(\omega_A t + \varphi_A) = \sin(\omega_A t + 0) = \sin(\omega_B t + \varphi_B)$$

$$\sin(\omega_A t) = 0 = \sin(\omega_B t + \varphi_B) \qquad \textbf{for} \quad \omega_A t = n\pi;\ n = 0, 1, 2, \ldots;\ n \in I+$$

Then, since $\omega_A = \omega_B$,

$$\sin(\omega_A t) = 0 = \sin(\omega_A t + \varphi_B)$$

$$\sin(\omega_A t) = 0 = \sin(\omega_A t)\cos(\varphi_B) + \sin(\varphi_B)\cos(\omega_A t)$$

$$\sin(n\pi) = 0 = \sin(n\pi)\cos(\varphi_B) + \sin(\varphi_B)\cos(n\pi)$$

$$0 = 0 = 0 + \sin(\varphi_B)(+/- 1)$$

$$0 = \sin(\varphi_B)(+/- 1)$$

$$0 = +/- \sin(\varphi_B)$$

Since $\varphi_B$ is periodic over $\pi$, $\varphi_B$ is equal to 0.

The above results indicate that **User A** and **User B** will both be trying to use the same slots at some point in the communication link ***E*** when the phase shift of **User B**

$$\varphi_B = 0$$

which is the phase shift of **User A** and that the two users will only intersect when the phase shifts of the two are the same.

As a more generic construction, consider when **User A** is characterized by $\sin(\omega_A t + \varphi_A)$ and **User B** is characterized by $\sin(\omega_B t + \varphi_B)$. Then

$$\sin(\omega_A t + \varphi_A) = 0 = \sin(\omega_A t + \varphi_B) \qquad \textbf{for } \omega_A t, \omega_b t = n\pi; n = 0,1, 2, ...; n \in I+$$

$$\sin(\omega_A t + \varphi_A) = 0 \text{ implies that } (\omega_A t + \varphi_A) = n\pi$$

and

$$\sin(\omega_A t + \varphi_B) = 0 \text{ implies that } (\omega_A t + \varphi_B) = n\pi$$

$$(\omega_A t + \varphi_A) = n\pi = (\omega_A t + \varphi_B)$$

The period under observation is when the two users are in the same frame, which will be when both ***n***s are the same. Setting them equal and subtracting like terms

$$\varphi_A = \varphi_B$$

and by definition the phase shift of the fundamental **User A** is zero.

The model for User A and User B with $\omega_A = \omega_B$ is

$$f(E) = \text{┼}\,(\sin(\omega_A t + \varphi_A) + \sin(\omega_B t + \varphi_B))$$

or

$$f(E) = \text{┼}\,(\sin(\omega_A t + \varphi_A) + \sin(\omega_A t + \varphi_B))$$

and in general, when more users enter the communication link with $\omega_A = \omega_i$

$$f(E) = \sum_{i=0}^{n} + ( \sin(\omega_A t + \varphi_i))$$

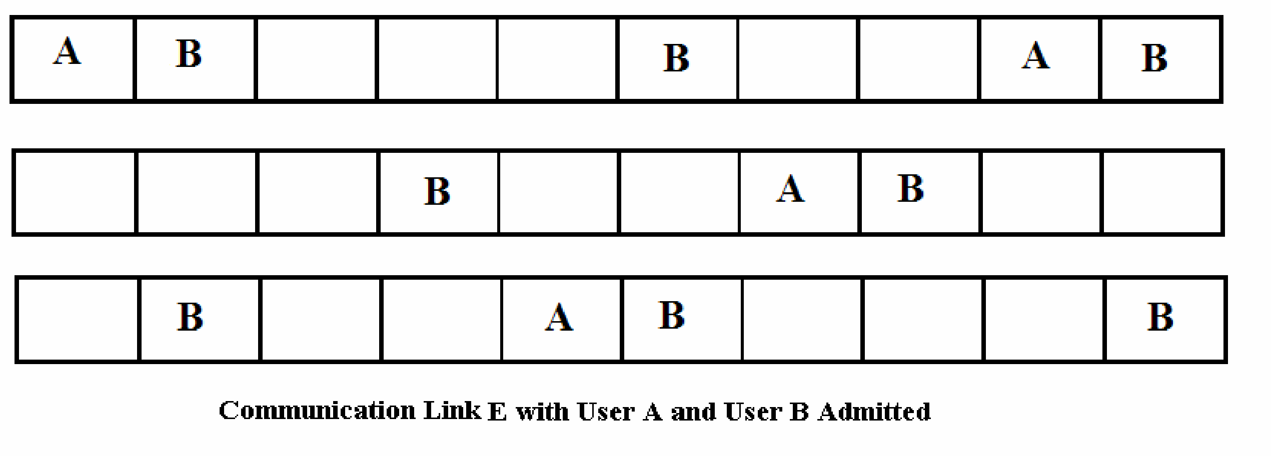
where all users appear as a phase shift relative to the fundamental user.

### 3.4.2. User B has an SD transmission frequency greater than User A

SD users with a transmission frequency $\omega_A$ greater than **User A** requesting admission to the link $E$ are broken down into two categories: those that have a transmission frequency $\omega_i$ that has $\omega_A$ as a multiplier and those $\omega_j$ of which $\omega_A$ is not a multiplier. The latter area is reviewed in Section **3.5**. The former area is the situation where the next user will be an SD user with a zero jitter requirement and the transmitted data will be inserted in the channel that meets the zero jitter requirement.

Once **User A** has been admitted to the link $E$, there is a maximum transmission frequency that the link $E$ can support relative to the next SD user requesting admission. The maximum allowable rate of the next SD user is dependent on $\omega_A$ and $n$, the transmission frequency of **User A** and the number of channels between successive transmissions by **User A**, respectively.

Shown in Figure 3.3 is a representation of **User B** joining **User A** in the communication link $E$. The representation shows **User B** with a transmission rate twice that of **User A**.



| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| A | B | | | | B | | | A | B |
| | | | B | | | A | B | | |
| | B | | | A | B | | | | B |

**Figure 3.3. Communication Link *E* with User A and User B Admitted**

With **User B** as the second user, utilizing one channel per data transmission and with ***n-1*** channels between successive transmissions of **User A**, the maximum transmission rate of the SD **User B** cannot be $n\omega_A$, as this will require utilization of the channel being used by **User A**. The maximum transmission rate for **User B** is then

$$(n\omega_A)/2 \qquad n \text{ is even}$$

This is shown in the example in Figure 3.4. In the example, the ***n*** is equal to 10.

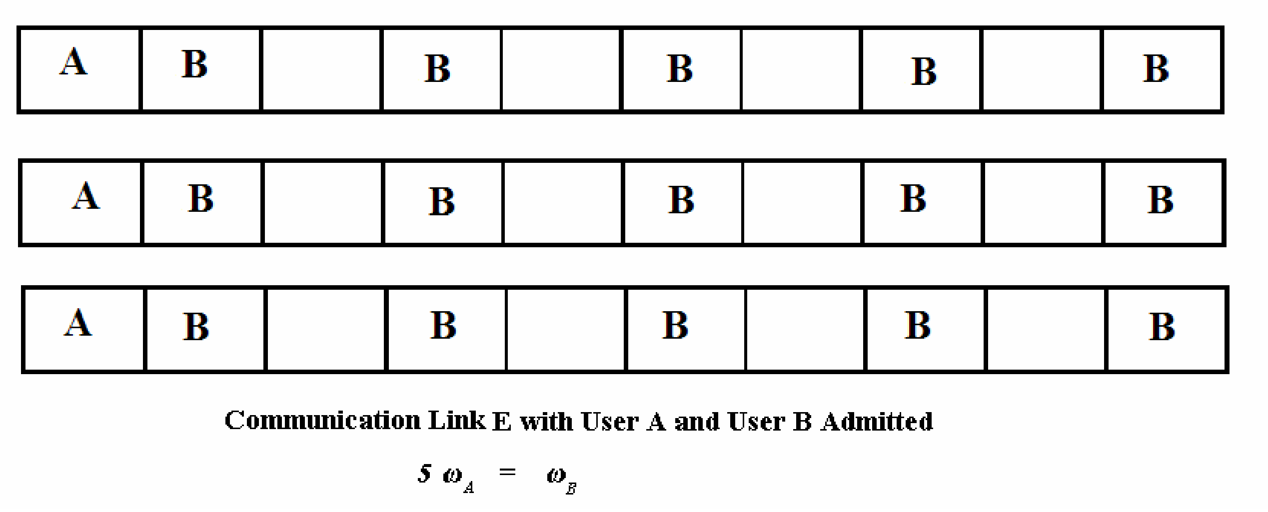


Figure 3.4. Communication Link *E* with User A and User B Admitted

Shown in Figure 3.5 is another example with User B transmitting at 2 times the frequency of User A.

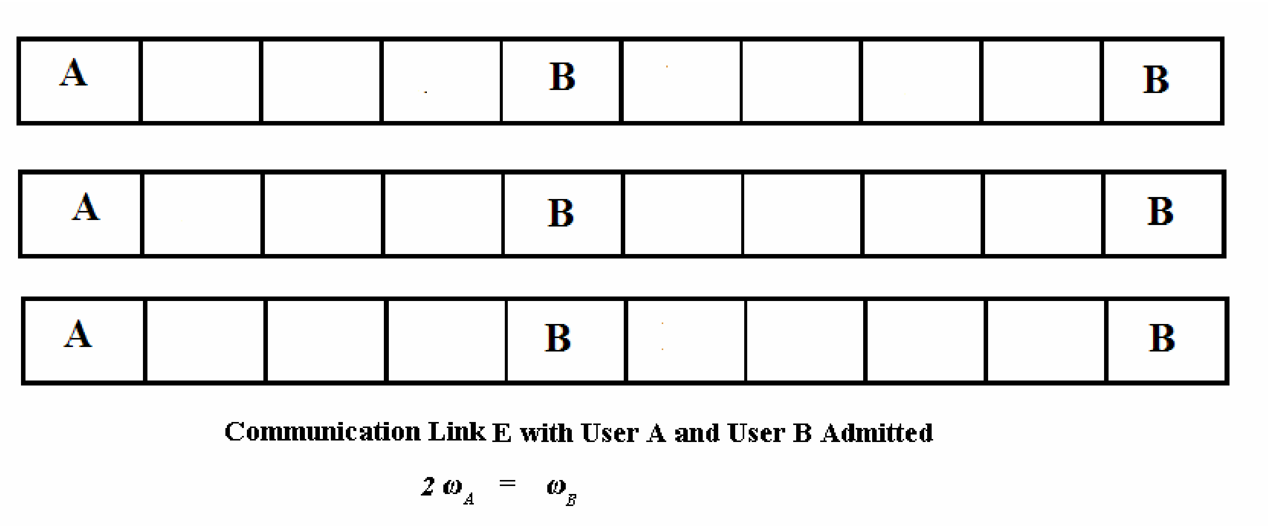


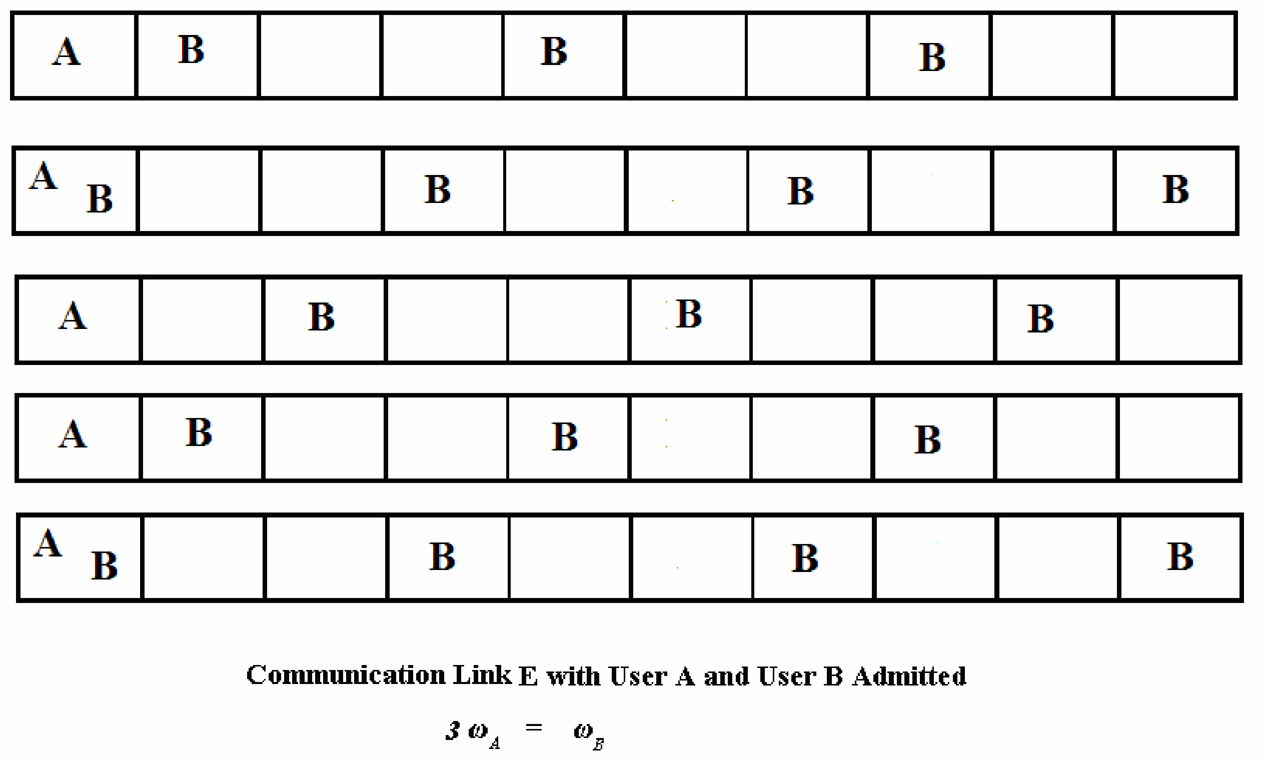
Figure 3.5. Communication Link *E* with User A and User B Admitted

In the two "zero-jitter allowed" SD examples shown above, with ***n*** equal to10, 2 times the fundamental and 5 times the fundamental fit evenly into the open channels without interfering with User A. In fact, 2 and 5 are the only values that will work because 10 is the lowest multiple of 2 and 5. In addition, $5\omega_A$ in this case is the highest transmission frequency that will be supported by the link when the users are zero jitter and zero delay SD users.

If $n = 3$ such that

$$3\omega_A = \omega_B$$

the resulting channel allocation would be



| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| A | B | | | B | | | B | | |
| A<br>B | | | B | | | B | | | B |
| A | | B | | | B | | | B | |
| A | B | | | B | | | B | | |
| A<br>B | | | B | | | B | | | B |

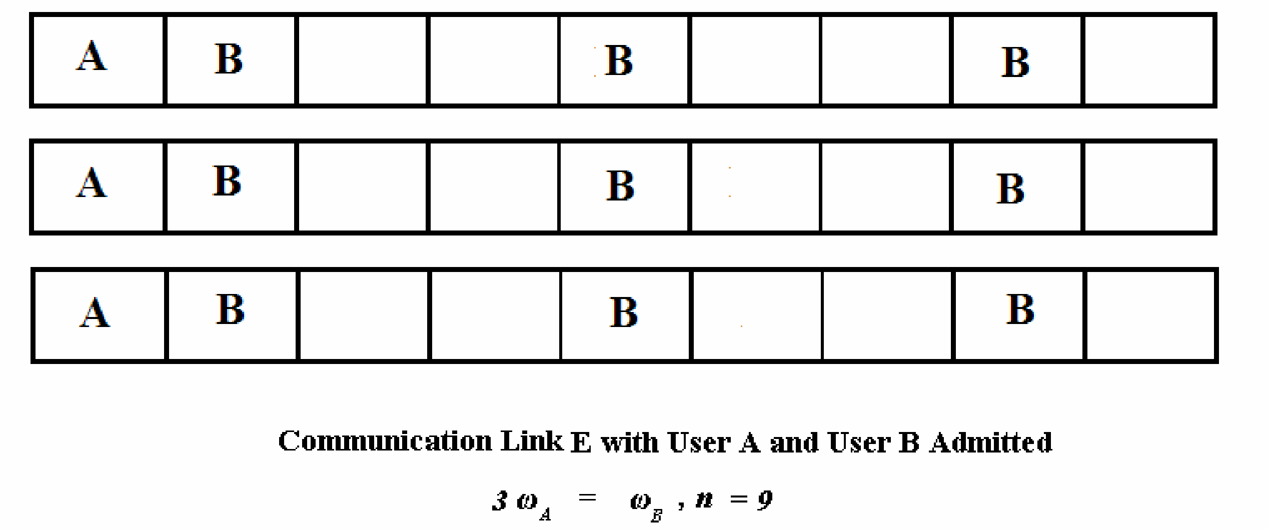
**Communication Link E with User A and User B Admitted**

$$3\,\omega_A = \omega_B$$

**Figure 3.6. Communication Link *E* with User A and User B Admitted**

The use of a non-multiplier of $n$ in this instance has introduced a collision in the communication link.

For the case where ***n*** is odd and not prime, the rule holds that the increase in the transmission rate of **User B** must have ***n*** as a multiple to avoid collisions of data transmissions for zero jitter and zero delay users. As and example, when $n = 9$ and ***n*** is the frame length**:**



| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| A | B | | | B | | | B | |
| A | B | | | B | | | B | |
| A | B | | | B | | | B | |

**Communication Link E with User A and User B Admitted**

$$3\,\omega_A = \omega_B \,,\; n = 9$$

**Figure 3.7. Communication Link *E* with User A and User B Admitted**

For the case shown above with an $n = 9$ the only faster transmission rate that will not cause a collision is when $\omega_B$ is three times faster than $\omega_A$.

By inspection it should be apparent that if **User B** has twice the transmission frequency of **User A** in the example above then collisions will occur, and this would be the same for any $\omega_B$ that is a multiple of 2, i.e., any even number.

The other case to consider is when the fundamental user has a transmission rate that causes the frame length ***n*** to be a prime number. Shown below is the case where $n = 13$.

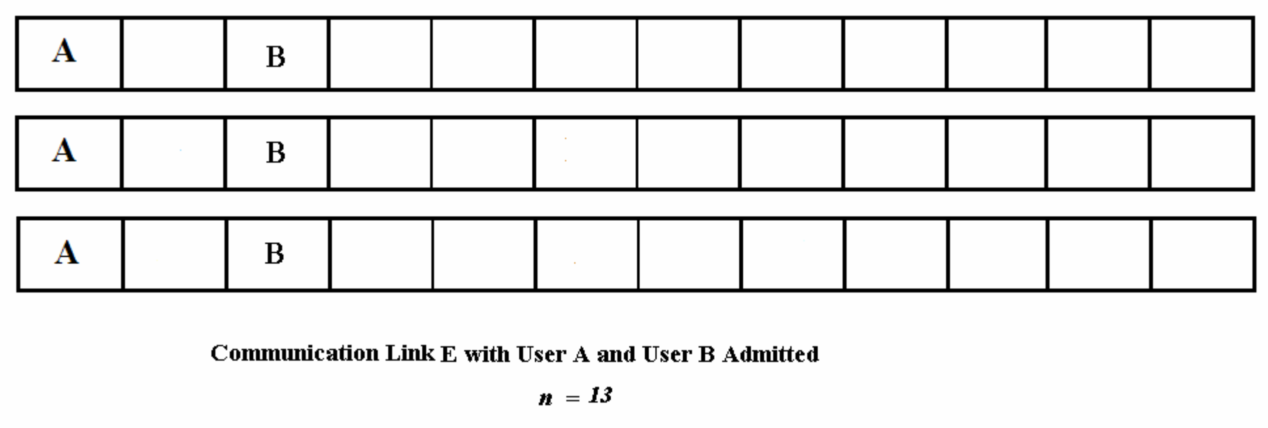


Figure 3.8. Communication Link *E* with User A and User B Admitted

From the previous example, where ***n*** is prime, the only transmission rate of **User B** that will not cause a collision is when $\omega_A = \omega_B$. The case where $n\omega_A = \omega_B$ is not allowed as it will cause a collision for **User A**.

Two constructions that be derived from the above examples are:

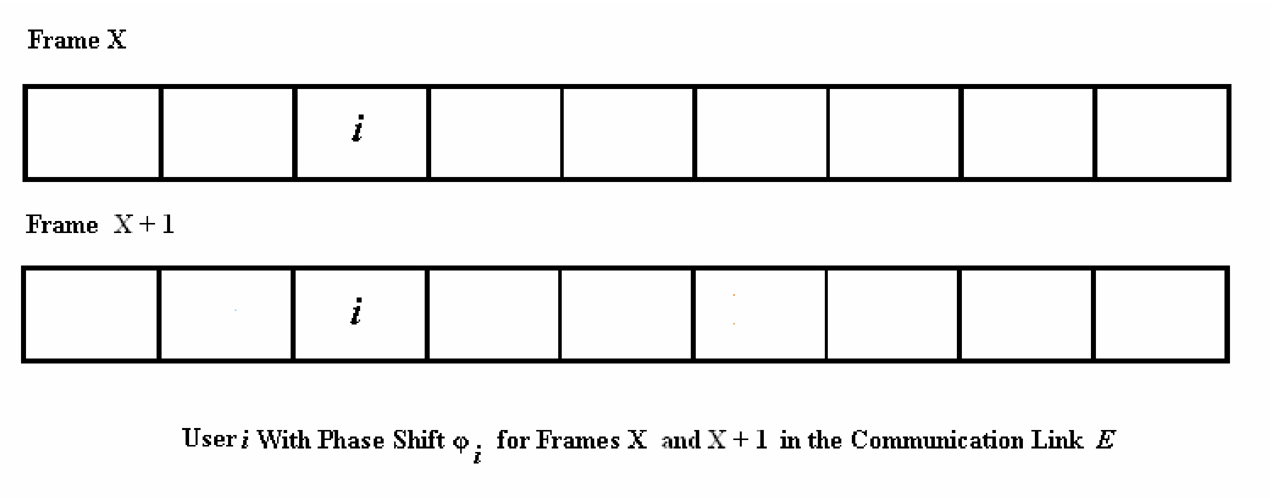
**Construction 1**: For the second SD, zero-jitter user requesting access to the communication link ***E***, only users with a transmission frequency $\omega_B$ that have ***n*** (the frame length, determined by $\omega_A$) as a multiple will map directly into the frames created by the transmissions of the fundamental user.

**Construction 2**: For the second SD, zero-jitter user requesting access to the communication link ***E***, the maximum transmission frequency $\omega_B$ that will map into the frames created by the transmissions of the fundamental user is the largest ***m*** that is a multiple of ***n*** (the frame length, determined by $\omega_A$).

The conditions of the communication link ***E*** require that an SD user with the zero-jitter requirement will have the same phase shift $\varphi_i$ relative to the fundamental user such that

$$\varphi_i^X = \varphi_i^{X+1}$$

where ***X*** and ***X + 1*** are frame identifiers used to signify successive frames in the communication link ***E***. This is shown in Figure 3.9.



User $i$ With Phase Shift $\varphi_i$ for Frames X and X + 1 in the Communication Link $E$

**Figure 3.9. User *i* with Phase Shift**

Since successive channels used by **User A** (the fundamental user, with a phase shift of zero) are ***n*** channels apart by definition such that

$$\sin\ (\omega_A^X\, t) = \sin\ (\omega_A^{X+1}(t+\delta))$$

relative to their location in the frame based on their zero phase shift, then successive frames containing transmissions by **User B** will also be ***n*** channels apart relative to **User A** such that

$$\sin\ (\omega_B^X\, t + \varphi_B^X) = \sin\ (\omega_B^{X+1}(t+\delta) + \varphi_B^{X+1})$$

because the position of each user transmission is represented as phase shift relative to the fundamental user. This is for the case when the user requirements do not allow delay and jitter. This is shown in Figure 3.10.

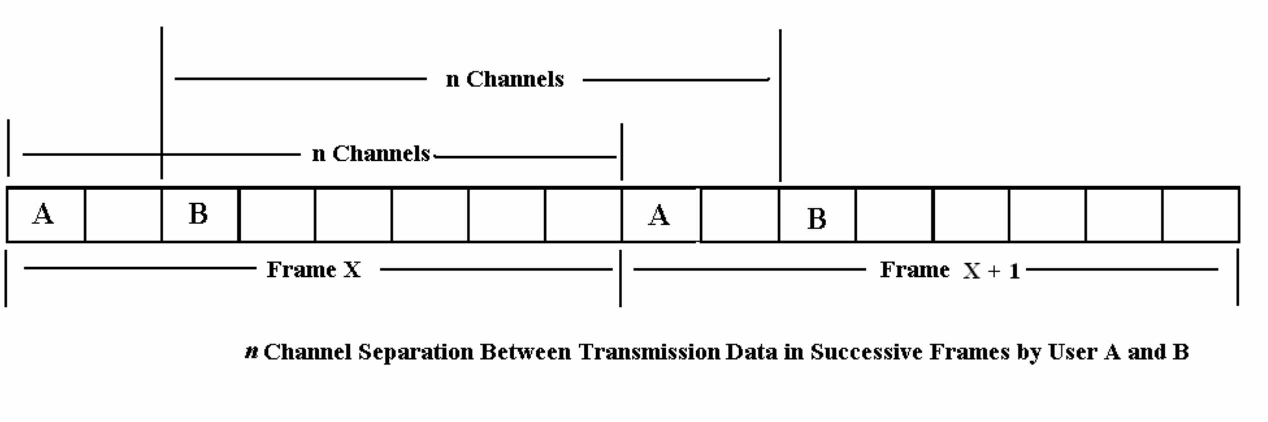


**Figure 3.10. *n* Channel Separation Between Transmission Data in Successive Frames by User A and B**

The SD user with a zero-jitter requirement and with the same requirements as **User A** in that the user is using only one channel per transmission will be transmitting at a fixed rate such that there are ***m*** occurrences of **User B** per frame. Furthermore, each occurrence of **User B** in successive frames will be ***n*** channels apart, which is shown in Figure 3.11, with the subscript on ***n*** indicating the user and the occurrence

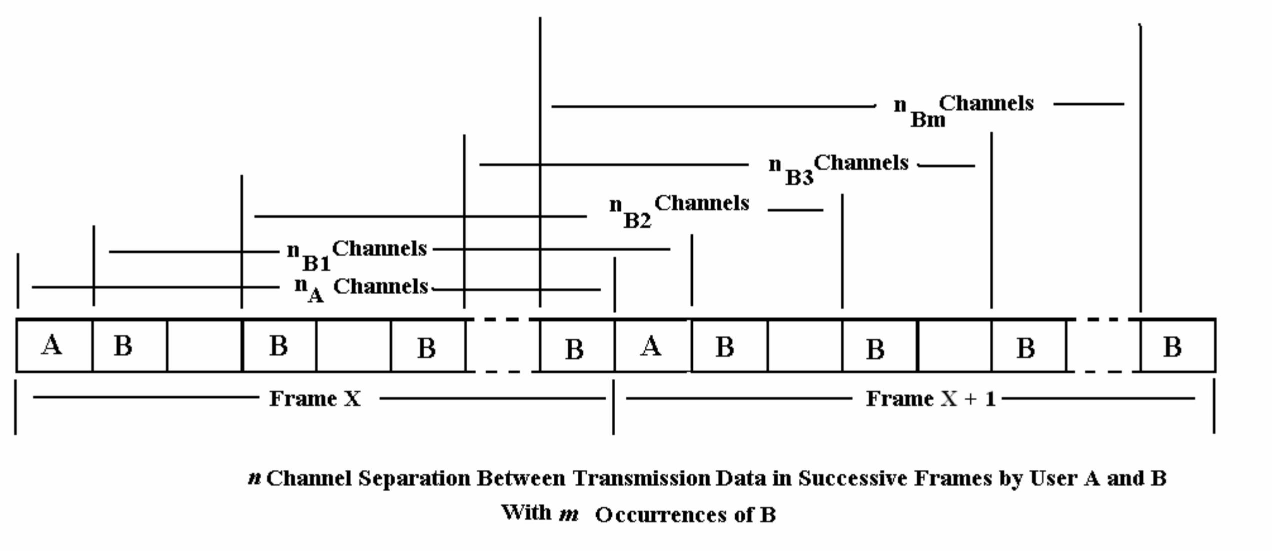


**Figure 3.11.** ***n*** **Channel Separation Between Transmission Data in Successive Frames by User A and B**

Since the channel size is fixed at ***n*** and the spacing between

$$B_1^X, B_2^X, \ldots, B_m^X$$

and

$$B_1^{X+1}, B_1^{X+1}, \ldots, B_m^{X+1}$$

is also ***n***, there then exists a ***k*** such that

$$k * m = n \qquad\qquad k, m, n \in I+$$

The largest value of ***m*** that has ***n*** as a multiple is the maximum number of occurrences of **User B** that will map evenly into the frame ***X***. The value $m\omega_A$ is the maximum transmission frequency of **User B** that will map evenly into the link ***E***, which supports constructions 1 and 2.

With the requirement that the SD user data map into a specific channel to avoid jitter, the admission of the fundamental user to the communication link $\boldsymbol{E}$ has placed restrictions on the transmission frequency of the second user. Similarly, the admission of the second user has further restricted the transmission frequencies of other users, given the same requirement.

**User B** can be represented by the notation

$$f(E_B) = \text{┼}\ \sin(\omega_B t + \varphi_B)$$

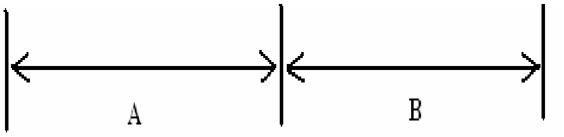
Since $\omega_B$ has $\omega_A$ as a multiple and it is only the zero-crossing that is required from the sine function to indicate a transmission by **User B**, **User B** can be represented as

$$f(E_B) = \sum_{i=1}^{n} \text{┼}\,(\sin(\omega_A t + \varphi_i))$$

with the multiple instances of **User B** represented as single instances of **User A** plus the phase shift for each instance (***n***) equal to the number of instances of **User B** in the frame.

The model for **User A** and **User B** with $n\omega_A = \omega_B$ is

$$f(E) = \text{┼}\,(\sin(\omega_A t + \varphi_A) + \sum_{i=1}^{n} \text{┼}\,(\sin(\omega_A t + \varphi_i)$$



and in general

$$\boldsymbol{f(E) = = {\Large +}\, (\, sin(\omega_A t + \varphi_A) + \sum_{j=1}^{m} \ \sum_{i=B}^{n} \ {\Large +}\, (\, sin(\omega_A t + \varphi_i)_j}$$

where ***n*** indicates the phase shifts of the individual users and ***m*** is indicates the user as additional users are granted access to the link.

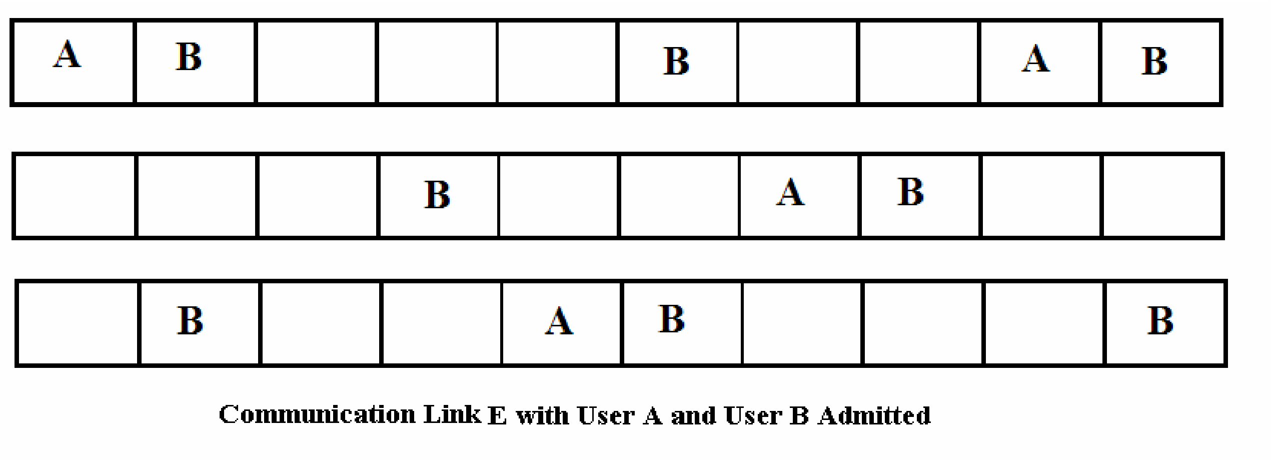
### 3.4.3. User B has an SD transmission frequency less than User A

The SD user requesting admission to the communication link that has a transmission frequency less than $\boldsymbol{\omega_A}$ can be divided into two categories: those that have ***n*** as a multiple and those that do not have ***n*** as a multiple. The first category will be covered here and the latter category is discussed in section 3.5.

As in the previous sections and examples, the other pre-conditions on the user requesting admission are that the user's information will only utilize one channel per transmission and the user has a zero-jitter requirement for data transmission. Multi-channel information is discussed in section 3.10, and jitter is discussed in Section 3.5

From the previous section, the fact that a user with a transmission frequency $\boldsymbol{\omega_A}$ has already been granted access to the communication link and $\boldsymbol{\omega_A}$ has as a multiple another transmission frequency $\boldsymbol{\omega_B}$ will allow the transmission frequency $\boldsymbol{\omega_B}$ to map directly into the communication link. This applies if $\boldsymbol{\omega_B}$ does not exceed the limitations on transmission frequency.

In this scenario, **User A** with transmission frequency $\boldsymbol{\omega_A}$ is the fundamental and **User B's** transmission frequency $\boldsymbol{\omega_B}$ is less than **User A's** transmission frequency. The fundamental frequency determines the frame length and is by design the transmission frequency that is supposed to be the least of the SD users in the communication link ***E***. To accommodate the admission of an SD user with a transmission frequency that is less than **User A's**, **User B** will be now be designated the fundamental user and **User A** will be considered as a user that has a transmission frequency that is a multiple of the fundamental, equating **User A** with **User B** in the previous section and vice-versa.



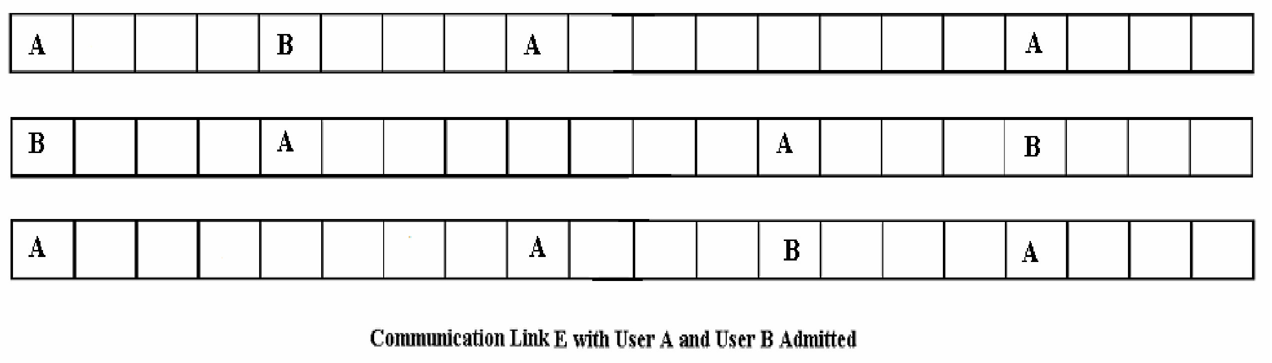
| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| A | B | | | | B | | | A | B |
| | | | B | | | A | B | | |
| | B | | | A | B | | | | B |

**Communication Link E with User A and User B Admitted**

**Figure 3.12. Communication Link *E* with User A and User B Admitted**

Figure 3.12 shows **User B** with a transmission frequency twice that of the fundamental **User A**.

Figure 3.13 is similar to Figure 3.12 in that there are two SD users transmitting their respective information in one channel per transmission, with one user transmitting at a rate that is twice that of the other. Except that now the user that is transmitting at twice the rate of the other is **User A**. The roles of **User A** and **User B** have been reversed, in that the original fundamental, **User A**, is now transmitting at twice frequency of **User B**.



Communication Link E with User A and User B Admitted

**Figure 3.13. Communication Link *E* with User A and User B Admitted**

For the scenario where a user with a transmission slower than the fundamental is requesting admission to the communication link, the following construction applies:

**Construction 3:** When a user is requesting admission to the communication link ***E*** and the user has a transmission rate $\omega_B$ that has $\omega_A$ (the fundamental frequency) as a multiple, the transmission frequency $\omega_B$ will be designated the fundamental frequency.

The model for the scenario where **User B** becomes the fundamental and **User A** is no longer the fundamental is the same as the model for the scenario where the transmission frequency of **User B** is a multiple of **User A**, except the indices are reversed. This is shown below.

$$f(E) = + ( \sin(\omega_B t + \varphi_B) + \sum_{i=1}^{n} + \sin(\omega_B t + \varphi_i))$$

and in general

$$f(E) = = + ( \sin(\omega_B t + \varphi_B) + \sum_{i=1}^{m} \sum_{i=A}^{n} + \sin(\omega_B t + \varphi_i)_j) \qquad \mathbf{m \neq B}$$

### 3.5 Non-Multiples of the Fundamental, Delay, and Induced Jitter

In the previous sections, only SD users with transmission frequencies that were multiples of the fundamental or had the fundamental as a multiple had been considered for entry into the communication link. This section will consider the admission to the link of those users that are not multiples of the fundamental or have the fundamental as a multiple.

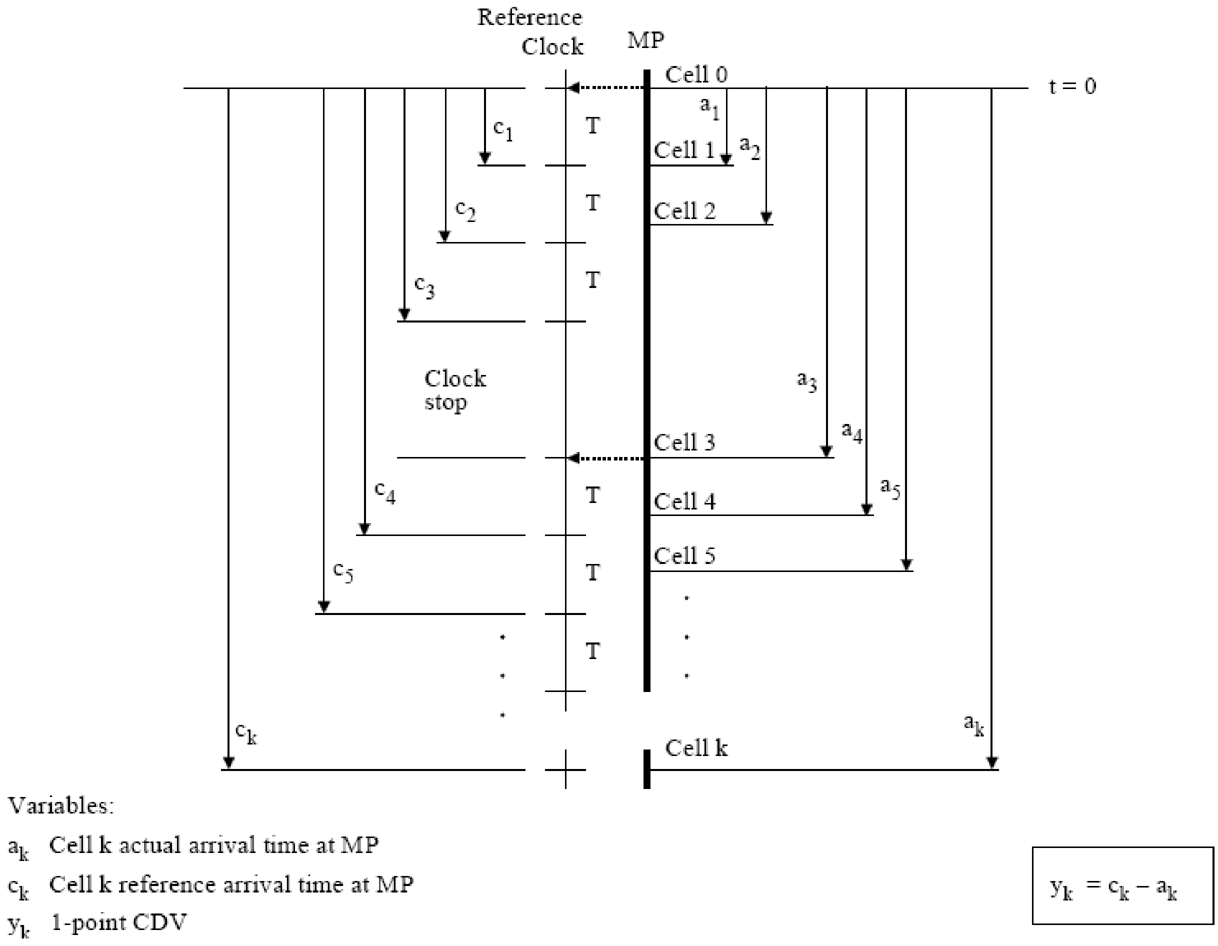
As discussed in Section 3.3, the admission of a user with a transmission frequency that is a non-multiple of the fundamental will eventually cause an interference with a previously admitted user. There are several possible methods for dealing with the non-multiple users:

1.) Don't admit the user.
2.) Require the user to modify its transmission frequency so that the frequency is a multiple of the fundamental or the fundamental of the user's transmission frequency.
3.) Drop a transmission from one of the users.
4.) Admit the user "as is" with the understanding of the complication (interference) that will result from admitting a user with a non-multiple transmission frequency.

Methods 1 and 2 do not alter the operation of the communication link other than to utilize channels in option 2. However, neither method may be acceptable to the user. Method 3 would be unacceptable for an SD connection with a zero loss requirement.

Option 4 potentially requires the data that is being transmitted in one channel to be moved to another channel. As shown previously in Figure 3.6, a non-multiple of the fundamental will cause a collision of users attempting to access the same channel. The movement of one of the user's transmitted data to another channel will introduce delay or jitter for that user. In the previous sections, only SD users with zero-jitter requirements were allowed to access the communication link. With the introduction of "non-multiple of the fundamental" SD users, allowance for delay and jitter must be considered.

The ITU-T defines 1-point cell delay variation as the "difference between the cell's reference arrival time ($c_k$) and actual arrival time ($a_k$)[38]." This is used for an ATM environment and is shown below where $y_k$ equals the cell delay variation or jitter.



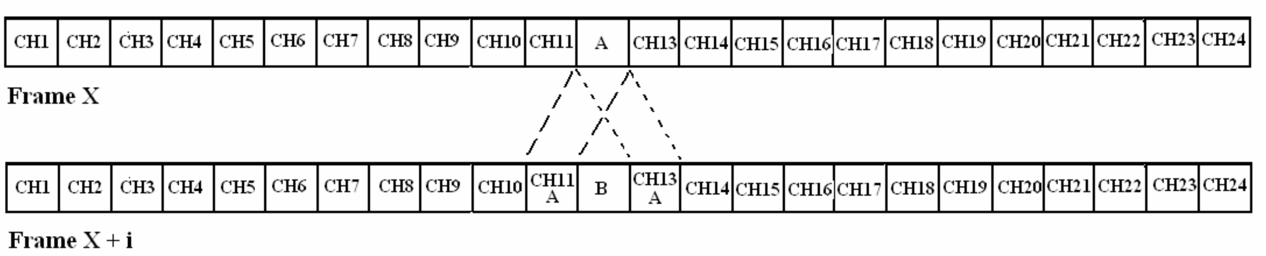
**Cell Delay Variation – 1-Point Definition**[39]

**Figure 3.14. Cell Delay Variation**

To be able to shift a user forward or backward into another channel (or cell), there must be unused channels available adjacent to or in the vicinity of the channel in question. In the figures shown in the previous sections, the number of channels between transmissions has been purposely kept small to demonstrate a concept. This would be similar to a standard T-1 communication channel.

The amount of delay and jitter in units of time depends on the transmission frequency of the link, the size of the transmission units, and how far away from the actual transmission slot the new transmission slot is located.

The forward and backward movements of **User A** are shown below with **User B** occupying the channel formally occupied by **User A**.



**User A Data in Channel 12, Frame X Being Moved to Either Chanel 11 or 13, Frame X + i to Accomodate User B**

**Figure 3.15. User A Data in Channel 12**

There is a fixed delay associated with the transmission of data that will include the time to transmit the data, as well as the time required to place the data into the channel and then remove it or propagate it on the other end. Since the SD link is synchronous sources, the re-location of information from one channel to another multiple times in different directions varies the delay and jitter is induced by the movement of data channels. The jitter requirements of the user will determine whether this introduction of jitter is acceptable. In terms of $y_k$, $c_k$, and $a_k$ the jitter is

$$y_k = c_k - a_k$$

$$y_k = t_{ref} + t_{fixed\ delay} - (t_{ref} + t_{fixed\ delay} + \Delta t)$$

$$y_k = -\Delta t$$

As an example, consider a 155.52 Mbps ATM link. The 155.52 Mbps has 366,792 cells, with 53 bytes per cell. An ATM bit is transmitted once every 6.43 ns, and a 53 byte cell is transmitted once every 2.73 μs. The relocation of a user's transmitted data forward or backward from the desired location will induce a jitter of ± 2.73 μs, depending on the direction of the relocation.

The model for the SD user that is experiencing jitter is no longer valid:

$$f(E_i) = \text{┼}\sin(\omega_i t + \varphi_i) \qquad \text{for} \quad 0 \le \omega_i t < 2\pi$$

$$\text{for} \quad 0 \le \varphi_i < \pi$$

For certain $t$s, the phase shift will vary either positively or negatively, and although it was reflected previously as only a single channel shift, it may be necessary to shift the transmitted data more that one channel.

One method to implement the phase shift is to only shift the user information when there will be collisions in frame **X**. In frames **X – 1** and **X + 1** there is no interference between **User B** and **User C**. This is shown in figure 3.16.

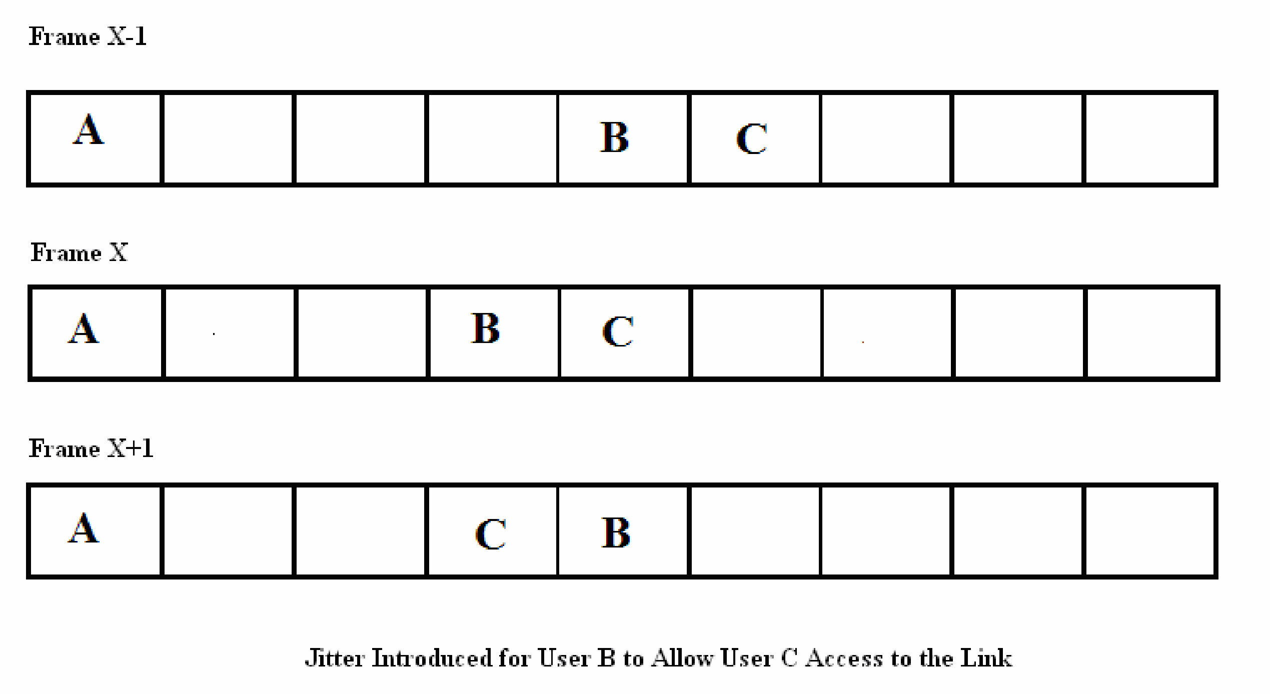


**Figure 3.16. Jitter Introduced for User B to Allow User C Access to the Link**

The figure above shows **User A** as the fundamental with transmission frequency $\omega_A$, User B with transmission frequency $\omega_B = \omega_A$, and **User C** with a transmission frequency $\omega_C$. with $\omega_C > \omega_A$, but transmitting at a frequency only slightly faster than **User A.** In this scenario, $\omega_C$ does not have $\omega_A$ as a multiple. **User B's** data transmission in frame **X** has been shifted to allow **User C** access to the channel, and then shifted back in frame **X + 1** to its original channel. This process would occur whenever **User C** has data to transmit and it needs access to the channel occupied by another user.

In this scenario, **User C** appears to be "sliding" through the frame, and will interfere with any user that is occupying a channel that **User C** needs to access, including the channel occupied by the fundamental user, which would occur in frame **X + 4**. Given the potential for interference with all of the users that have been granted access, **User C** is this case might be rejected for admission to the link.

The characteristic notations for **Users A, B**, and **C** can be demonstrated by setting $\tau$ as the time between frames and $\delta$ as the time a channel is transmitted, the latter being equivalent to a zero-crossing of the characteristic equation. The transmission of frame **X** occurs at a relative time of $t = 0$. In this example, the characteristic equations for Users A, B, and C are based on the frame being nine channels long, as shown in Figure 3.16.

The model for **User A**, the fundamental user, in this scenario, is the same as it was originally:

$$f(E_A) = +(\sin(\omega_A t + \varphi_A)) = +(\sin(\omega_A t)) \quad \textbf{for} \quad 0 \le \omega_A t < 2\pi \qquad t \ne 4\tau, 12\tau, 20\tau, \ldots$$

$$\textbf{for} \quad 0 \le \varphi_A < \pi$$

***and***

$$f(E_A) = +(\sin(\omega_A t + \varphi_{A+1})) \quad \textbf{for} \quad 0 \le \omega_A t < 2\pi \qquad t = 4\tau, 12\tau, 20\tau, \ldots$$

$$\textbf{for} \quad 0 \le \varphi_A < \pi$$

The model for **User B** is (remembering $\omega_A = \omega_B$):

$$f(E_B) = +\sum_{i=1}^{n} +(\sin(\omega_A t + \varphi_B)) \quad \textbf{for} \quad 0 \le \omega_A t < 2\pi \;, t \ne 4\delta, 8\tau + 4\delta, 16\tau + 4\delta, \ldots$$

$$\textbf{for} \quad 0 \le \varphi_B < \pi$$

and

$$f(E_B) = +\sum_{i=1}^{n} +(\sin(\omega_A t + \varphi_{B-1})) \quad \textbf{for} \quad 0 \le \omega_A t < 2\pi \;, t = 4\delta, 8\tau + 4\delta, 16\tau + 4\delta, \ldots$$

$$\textbf{for} \quad 0 \le \varphi_B < \pi$$

The model for **User C** is:

$$f(E_C) = +\sum_{i=1}^{n} \left( \sin(\omega_A t + \varphi_{A+4}) \right) \quad \textbf{for} \quad 0 \leq \omega_A t < 2\pi \;, t = 4\delta,\ 8\tau + 4\delta,\ 16\tau + 4\delta,\ \ldots$$

$$f(E_C) = +\sum_{i=1}^{n} \left( \sin(\omega_A t + \varphi_{A+3}) \right) \quad \textbf{for} \quad 0 \leq \omega_A t < 2\pi \;, t = \tau + 3\delta,\ 9\tau + 3\delta,\ 17\tau + 3\delta,\ \ldots$$

$$f(E_C) = +\sum_{i=1}^{n} \left( \sin(\omega_A t + \varphi_{A+2}) \right) \quad \textbf{for} \quad 0 \leq \omega_A t < 2\pi \;, t = 2\tau + 2\delta,\ 10\tau + 2\delta,\ 17\tau + 3\delta,\ \ldots$$

***etc.***

In a different scenario, another possibility to handle delay and jitter would be to shift **User B's** transmissions to a different channel and leave it in the new channel until User C needs the new channel occupied by User B, at which point User B is moved back to its original channel. This is shown in Figure 3.17.

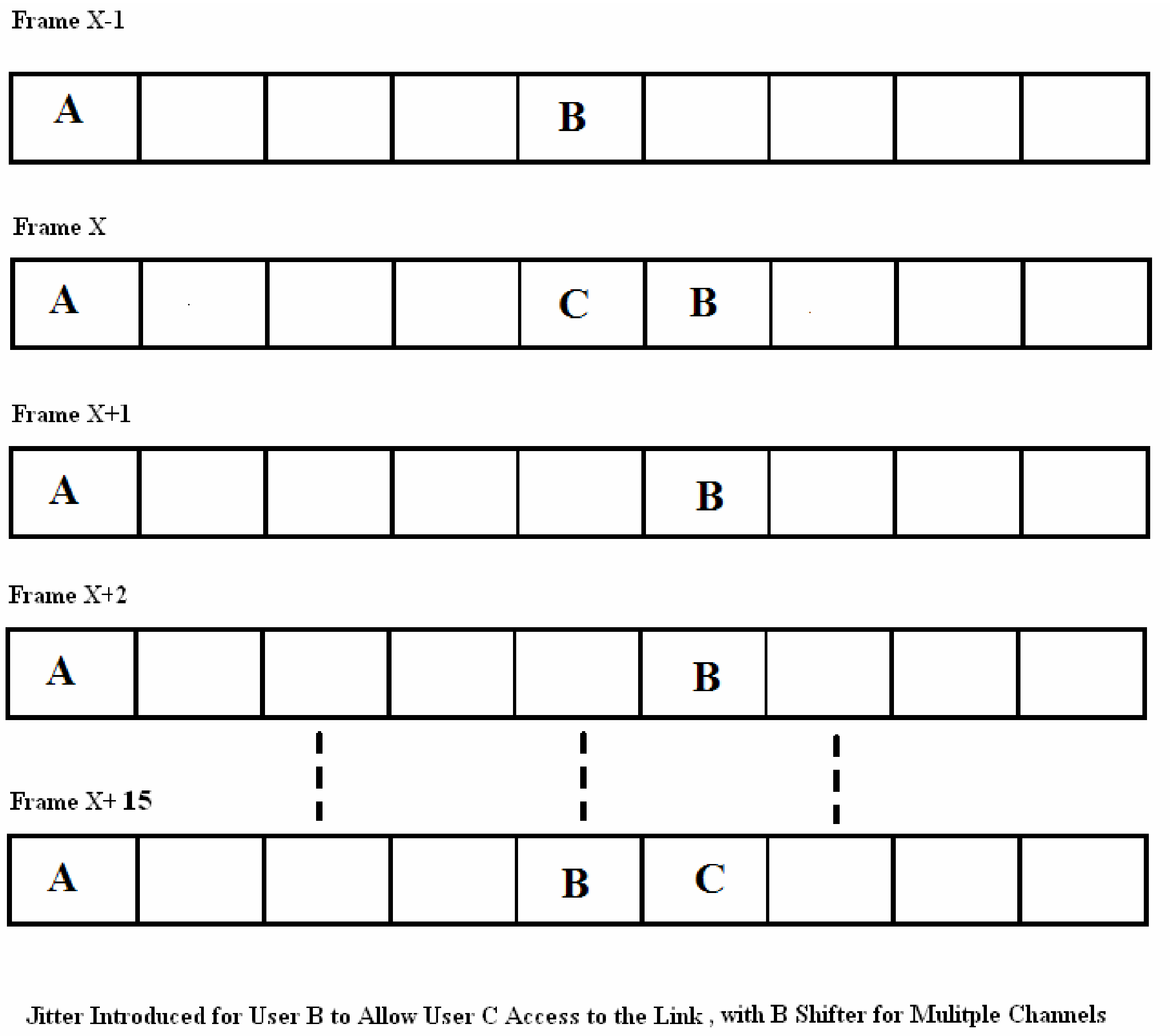


**Figure 3.17. Jitter Introduced for User B to Allow User C Access to the Link**

The effect of this method is to introduce delay for **User B** but to limit jitter.

## 3.6 OPTIMUM FRAME SIZE

The frame size is determined by the transmission frequency of **User A**, the fundamental user, and each transmission by **User A** marks the beginning of a new frame. As was shown previously, subsequent users will be affected by the frame size that is determined by the fundamental user.

The frame size is user determined in that the fundamental user need not be the first user that requests admission to the link. In addition, the channel size is adjustable, which makes it possible to increase the number of channels in the frame to better accommodate other users.

For example, let the number of bits required by **User A** be 10 bits per transmission, the number of bits per channel be 20, and the number of bits per frame be 200, so that there are 10 channels per frame. Subsequent users will limited to the 9 channels that are unused and must have 10 as a multiple to fit evenly into the frame.

If the channel size were decreased to 10 bits per channel, the number of channels per frames is now 20, and subsequent users will need to have 20 as a multiple to fit evenly into the frame. In addition, there are more frames available to service users.

The optimum frame size is left for future research.

## 3.7 FINITE USERS

The finite user is defined as an SD user that will transmit information for a pre-determined fixed length of time. An example of a finite SD user is shown in Figure 3.18.

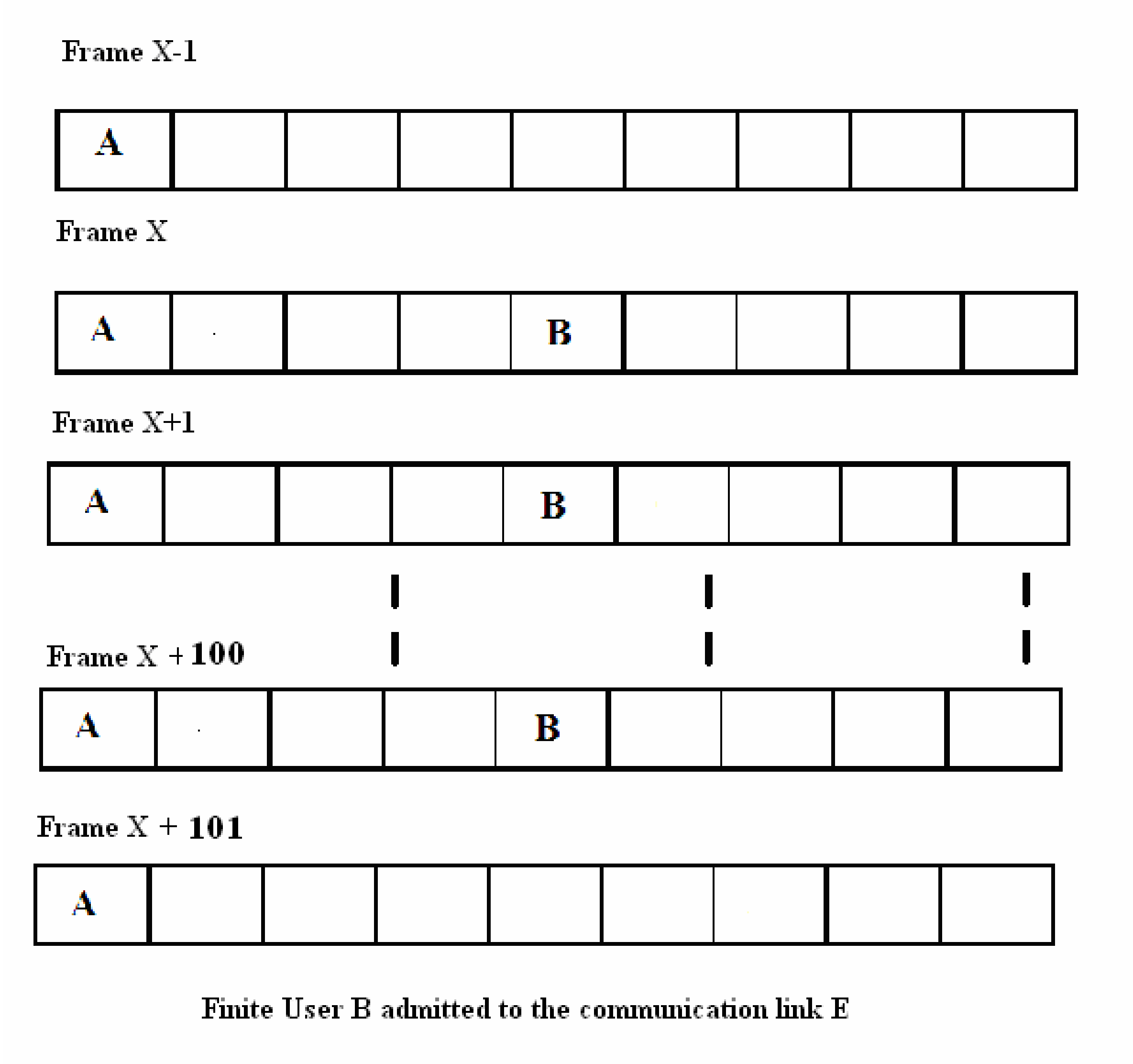


**Figure 3.18. Finite User B Admitted To The Communication Link *E***

The model for the finite SD user is similar to the model for the continuous SD user, except there are bounds on ***t***. The model for the other non-finite users will remain the same. The finite user model is shown below.

$$f(E_B) = \text{┼}\,(\sin(\omega_A t + \varphi_B)) \qquad \textbf{for} \quad 0 \le \omega_A t < 2\pi$$

$$\textbf{for} \quad 0 \le \varphi_A < \pi$$

$$\text{for } t_1 \le t \le t_2$$

In the example above $\omega_A = \omega_B$ and the frames in the window **X** to **X + 100** are as they would appear if User B were a continuous user.

For the case where $\omega_B$ is $n$ times $\omega_A$ the communication link $E$ would appear as in Figure 3.19.

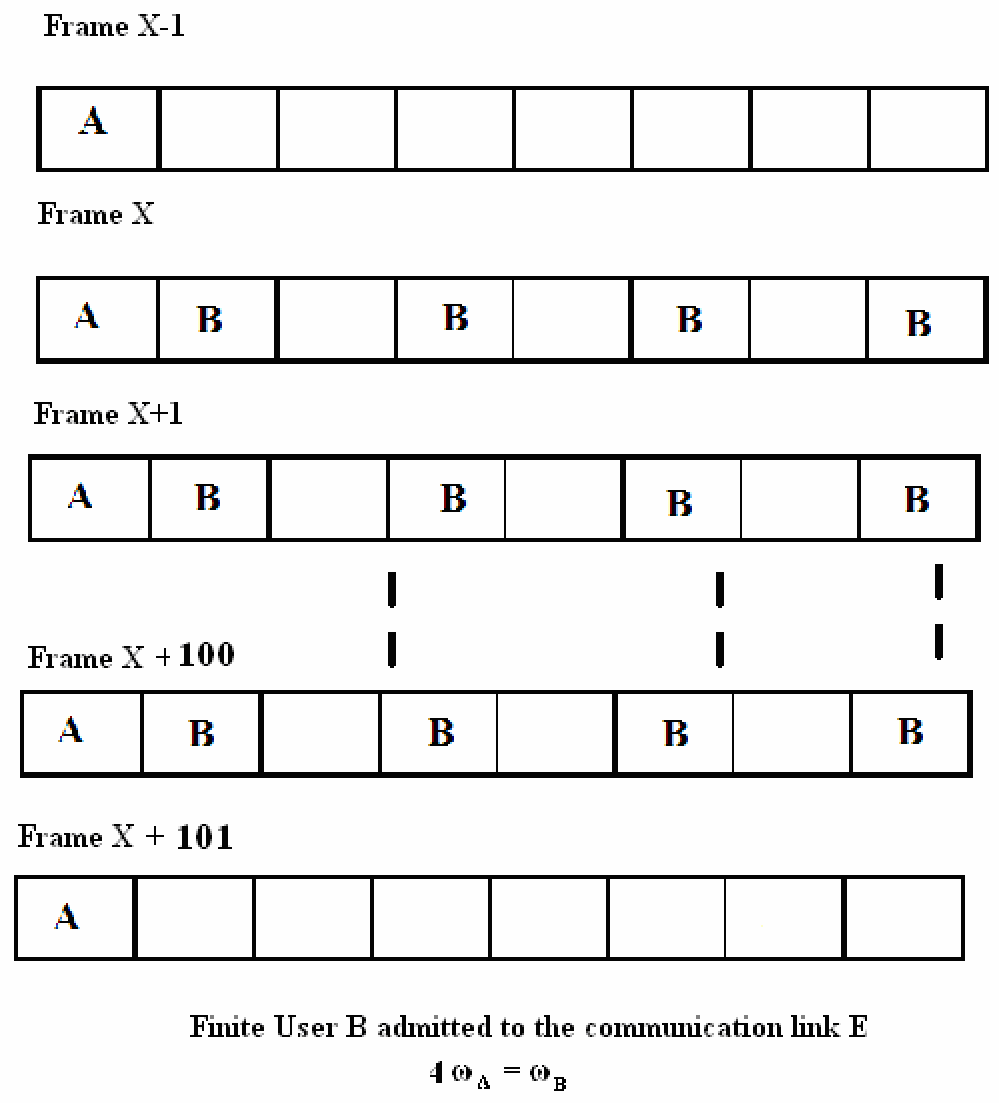


**Figure 3.19. Finite User B Admitted To The Communication Link *E***

In the example above $\omega_B = 4\omega_A$ and the frames in the window **X** to **X + 100** are as they would appear if User B were a continuous user. The model for **User B** would be

$$f(E_B) = + [( \sin(\omega_A t + \varphi_{B1}) + ( \sin(\omega_A t + \varphi_{B2})$$

$$+ ( \sin(\omega_A t + \varphi_{B3}) + ( \sin(\omega_A t + \varphi_{B4})] \qquad \text{for} \quad 0 \le \omega_A t < 2\pi$$

$$\text{for} \quad 0 \le \varphi_A < \pi$$

$$for\ t_1 \le t \le t_2$$

The finite user could be an example when jitter would be induced for consecutive frames instead of just a single frame where the user would be shifted back after one frame as was shown in the section on jitter. This is shown in Figure 3.20.

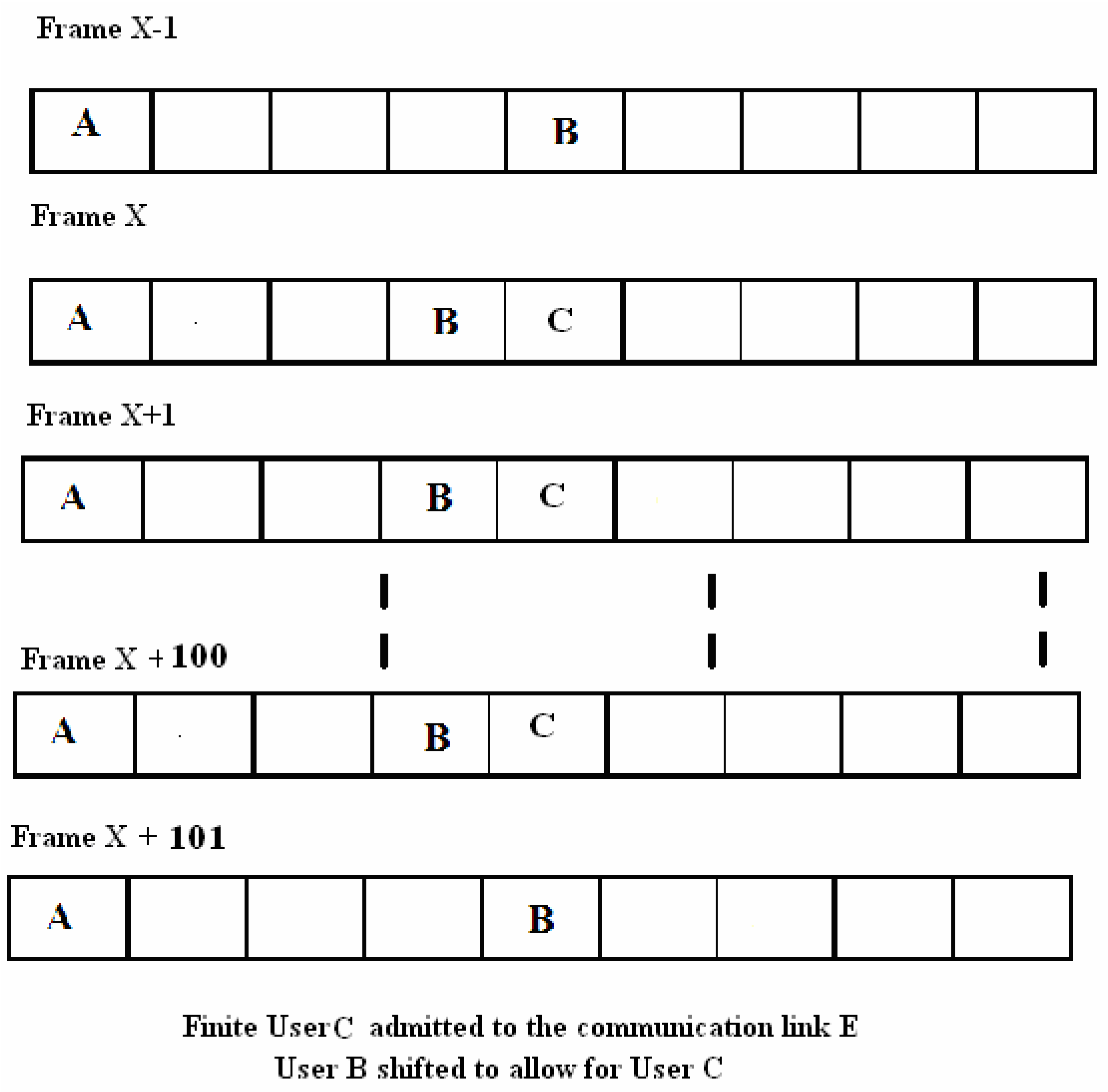


**Figure 3.20. User B Shifted To Allow For User C**

In the above example, **User B** has been shifted to allow **User C**, a finite user, access to the channel. This situation would occur when **User C** has a zero-jitter requirement and **User B** is allowed some jitter.

The model for both **User B** and **User C** would be same as the continuous SD user for the frames in the window **X** to **X + 100**, as is shown below.

$$f(E_B) = + ( \sin(\omega_A t + \varphi_{i-1})) \qquad \text{for} \quad 0 \le \omega_A t < 2\pi$$

$$\text{for} \quad 0 \le \varphi_A < \pi$$

$$\text{for } t_1 \le t \le t_2$$

$$f(E_C) = + ( \sin(\omega_A t + \varphi_i)) \qquad \text{for} \quad 0 \le \omega_A t < 2\pi$$

$$\text{for} \quad 0 \le \varphi_A < \pi$$

$$\text{for } t_1 \le t \le t_2$$

In the last example above, **User B** and **User C** both have the same transmission frequency as **User A**.

As shown in the examples above, the case for the finite SD user in the window of transmission indicates the model would be the same as the continuous user. The case for the non-multiples of the fundamental would also be the same. The case for the non-multiple of the fundamental would also be the same and is left as future research.

### 3.8 NON-SD USERS

Non-SD users are characterized as users that transmit aperiodic, non-uniform amounts of data that have no restrictions on delay, jitter, or loss.

These users will be mapped into channels not required for use by SD users. In Figure 3.21, **User N** has been given access to the unoccupied channels.

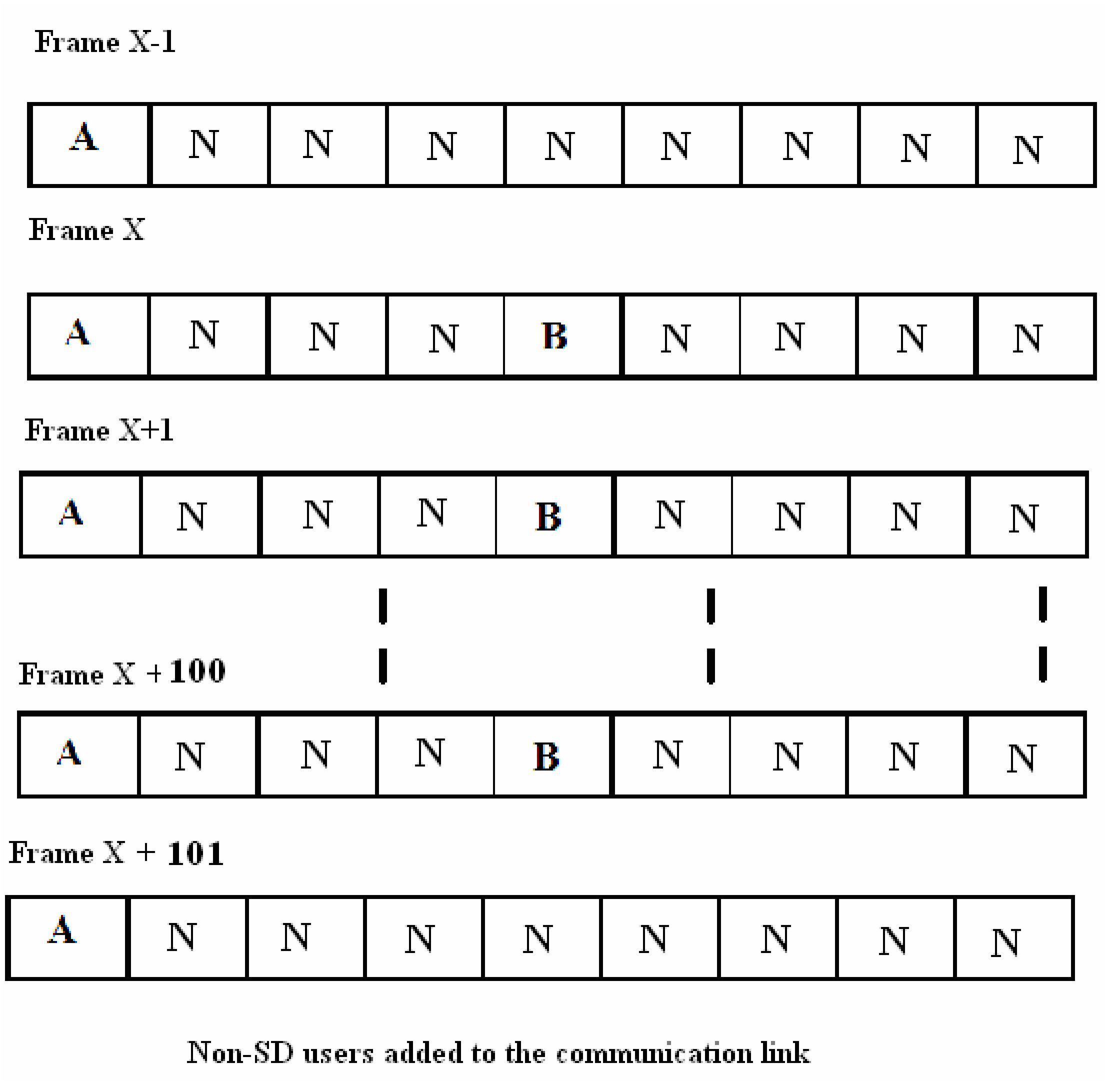


**Figure 3.21. Non-SD Users Added to the Communication Link**

The non-SD user can be modeled as an SD user similar to the SD user. This is shown below.

For frames prior to **Frame X**:

$$f(E_N) = + \sum_{i=1}^{n} + ( \sin(\omega_A t + \varphi_i))$$

for $0 \leq \omega_A t < 2\pi$

for $0 \leq \varphi_i < \pi$

$for\ t < t_1$

For **Frame X** to Frame **X + 100**:

$$f(E_N) = + \sum_{i=1}^{n} + ( \sin(\omega_A t + \varphi_i))$$

$n \neq 5$

for $0 \leq \omega_A t < 2\pi$

for $0 \leq \varphi_i < \pi$

$for\ t_1 \leq t \leq t_2$

And for frames after **Frame X + 100**:

$$f(E_N) = + \sum_{i=1}^{n} + ( \sin(\omega_A t + \varphi_i))$$

for $0 \leq \omega_A t < 2\pi$

for $0 \leq \varphi_i < \pi$

$for\ t_2 < t$

## 3.9 USERS THAT REQUIRE MORE THAN ONE CHANNEL PER TRANSMISSION

All of the previous examples have been of users that were able to fit their data transmissions into one channel. Shown below is a representation of **User B,** with the user requiring more than one channel for transmission.

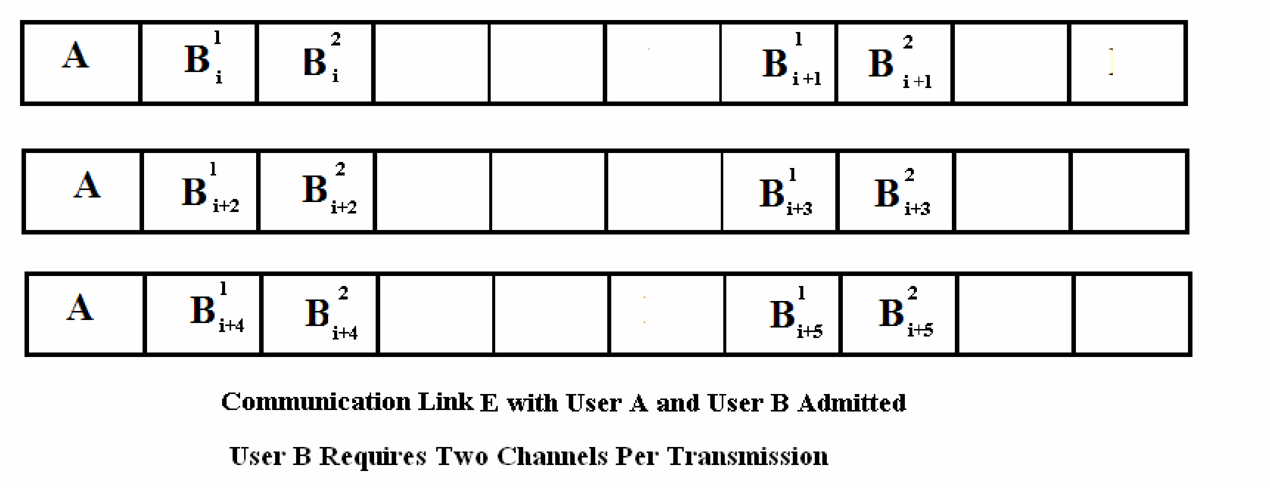


**Figure 3.22. User B Requires Two Channels Per Transmission**

Figure 3.22 shows **User A** as the fundamental and the ***ith*** through ***ith + 5*** transmissions of **User B** with $\omega_B = 2\,\omega_A$. User B also requires two channels per transmission, indicated by the superscripts **1** and **2**.

The transmissions shown above in Figure 3.22 would be comparable to having **User B's** two-channel transmission represented by single-channel transmissions by **User D** and **User G**.

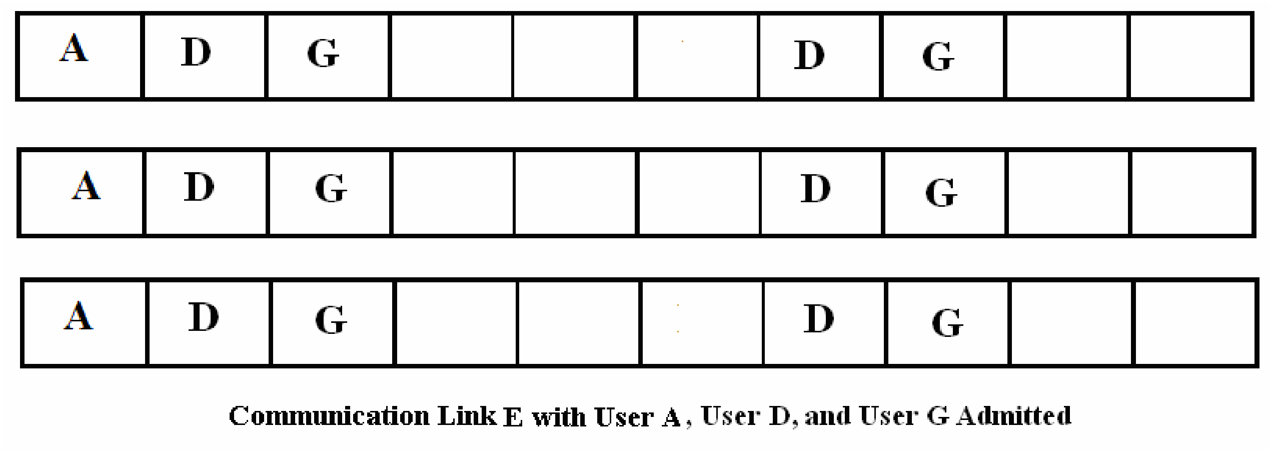


**Figure 3.23. Communication Link *E* with User A, User D, and User G Admitted**

The model for the above transmission would be

$$f(E) = \text{┼}\,(\sin(\omega_A t + \varphi_A)) + \text{┼}\,(\sin(\omega_D t + \varphi_D)) + \text{┼}\,(\sin(\omega_E t + \varphi_G))$$

and since $2\omega_A = \omega_D = \omega_E$ the above model can be represented as:

$$f(E) = \text{┼}\,(\sin(\omega_A t + \varphi_A) + \text{┼}\,(\sin(\omega_A t + \varphi_{D1}) + \text{┼}\,(\sin(\omega_A t + \varphi_{G1})$$

$$+ \text{┼}\,(\sin(\omega_A t + \varphi_{D2}) + \text{┼}\,(\sin(\omega_A t + \varphi_{G2})$$

Similarly, the two-channel transmission of **User B** can be represented as

$$f(E) = \text{┼}\,(\sin(\omega_A t + \varphi_A) + \text{┼}\,(\sin(\omega_B t + \varphi_{B1}) + \text{┼}\,(\sin(\omega_B t + \varphi_{G2})$$

and then:

$$f(E) = \text{┼}\,(\sin(\omega_A t + \varphi_A)) + \text{┼}\,(\sin(\omega_A t + \varphi_B{}^{1}{}_{1})) + \text{┼}\,(\sin(\omega_A t + \varphi_B{}^{2}{}_{1}))$$

$$+ \text{┼}\,(\sin(\omega_A t + \varphi_B{}^{1}{}_{2})) + \text{┼}\,(\sin(\omega_A t + \varphi_B{}^{2}{}_{2}))$$

# 4.0 THE ADMISSION CONTROL METHODOLOGY

The Admission Control Methodology, sometimes referred to as the Connection Admission Control Algorithm (CAC) or the Call Admission Control Algorithm, is the method by which users are granted access to the network, or in this case, the communication link. The corresponding analogous algorithm of this research is the methodology by which a decision is made to admit or not admit a user to the link. As will be described in this chapter, the link and the set of potential users will be defined by a state diagram with a set of probabilities as to the users that will likely appear for admission. Each state represents the current set of users on the link, i.e., the link environment. Changes in state are determined by users being added to or removed from the link. Each new user will cause the system to change state although one possibility is the return to the current state. For example, a user with the same frequency and only a shift in phase from the fundamental would not represent a transition to a new state, but rather it would constitute a transition to the same state. However, the transition is important to update the link environment. Based on all state transitions, it is possible to determine a figure of merit based on regards for making each state transition. This is the reward mechanism

The primary decision at any point in time is whether to admit a user request that results in a trapping state. If the user does not result in a trapping state transition, and all characteristics are satisfied, the user is admitted. If admission of the user would result in a trapping state, the rewards based on this decision are used to determine the gain of the system in the resulting trapping state which can be compared against the probability of receiving a request from a user that would result in the other trapping state. All of the mathematical development to carry out this method of determining user access that is equivalent to the term algorithm of the other link formulations will be presented in this chapter[40].

For a user’s transmissions to be accepted for transmission by the communication link, the user’s transmissions must be formatted to fit into the characteristic model

$$+ (\sin(\omega_i t + \varphi_i)) \qquad \text{for} \quad 0 \le \omega_i t < 2\pi$$

$$\text{for} \quad 0 \le \varphi_i < \pi$$

Each user’s transmission will be placed into a frame that is defined by the transmissions of the fundamental user. The locations of the new user’s data transmissions in the frame after the selection of the fundamental user are identified by a phase shift relative to the channel (transmissions occurring at the zero crossings) that is allocated to the transmission of the fundamental user.

The Admission Methodology is divided into three components:

1.) The first component will evaluate users that are requesting access to the link when the link is empty, i.e., to become the fundamental user.

2.) The second component evaluates subsequent users after the fundamental user has been granted access.

3.) The third component will examine the requirements of placing the user into the frame, based on the transmission requirements of the user. These are examined in the following sections.

## 4.1 ADMISSION FOR THE FUNDAMENTAL USER

The primary purpose of the communication link ***E*** is to maximize the usage of link ***E***, fundamentally in support of users with Synchronous Dependent requirements. The selection of the fundamental user should maximize the probability of selecting a user that will enhance this purpose.

The fundamental user's transmissions are used to initially define the frames in the communication link. The fundamental user must appear to transmit at a fixed frequency to maintain the frame size. Users that will enter the link after the fundamental user will be located in the frames by referencing their position relative to the fundamental, with the reference to the fundamental in the form of a phase shift. The fundamental user must also appear to be a continuous user, for the purpose of defining the length of the frames.

The fundamental user will be characterized and identified by the octuple

$$[\ \mathbf{U_i}\ ] = (\boldsymbol{P\ or\ non\text{-}P},\ \boldsymbol{c},\ \boldsymbol{\rho},\ \boldsymbol{\alpha},\ \boldsymbol{\delta},\ \boldsymbol{j},\ \boldsymbol{B},\ \boldsymbol{hh.mm.ss.hs.ts})$$

It is not one parameter that makes the user's request Synchronous Dependent (SD), but rather the combination of the need for the first six parameters of the above octuple to be met. The seventh parameter is in support of non-SD traffic. The eighth can be viewed as an optional element towards SD compliance in support of Hard Real-Time control systems. These parameters are discussed in the following sections as they relate to the admission of the fundamental user.

### 4.1.1. Periodic or non-periodic

The first parameter is the type of data the fundamental user will be transmitting, i.e., is it periodic or non-periodic, represented by ***P*** and ***non-P,*** respectively. The fundamental user will normally be transmitting periodically, unless the non–SD user's transmissions are configurable as periodic, which may be advantageous under certain circumstances. The fundamental will appear as a periodic user to maintain the framing for the link.

### 4.1.2. Continuous or non-continuous

The second parameter, **c**, indicates whether the user's data transmissions are continuous or non-continuous (finite). With respect to the fundamental user, if a non-continuous, or finite, user is chosen as the fundamental user and the user terminates transmission, a "pseudo-user" of comparable characteristics will be used to maintain the frame size until another user of suitable characteristics is chosen.

### 4.1.3. Frequency of transmission

The third parameter of the octuple is the frequency of the transmission, represented by $\boldsymbol{\rho}$**.** The units for $\boldsymbol{\rho}$ are in transmissions per unit time.

As discussed in Chapter 3, the frequency of transmission of users already granted access to the link will affect the other users that are admitted to the communication link.

The significance of the frequency of transmission for the fundamental is related to how many channels there are in between successive channels of the fundamental. As shown in Chapter 3, subsequent users can be either multiples or non-multiples of the fundamental. If the subsequent users do not have transmission frequencies that are multiples of the fundamental, jitter and delay are induced.

If the frequency of transmission of the fundamental is such that the number of channels between the end of the ***ith*** transmission and the end of the ***ith* + *1*** transmission is a prime number ***a***, then only a subsequent user with a transmission frequency that is ***a*** will not induce jitter or delay

As discussed in Chapter 2, the advantage of the SD link is that the channels can be resized such that the number of channels need not be a prime number. The channel size is a function of the data being transmitted by the user, the frequency of the transmission, and the total transmission frequency of the link. By making the channel larger, there are fewer channels per frame, and the user transmission frequency may allow for an even number of channels per frames as opposed to a prime number of channels.

### 4.1.4. Amount of data per unit time

The fourth parameter is represented by $\alpha$. For SD traffic this indicates the amount of data in bits being transmitted per period. The importance of this parameter is in the sizing of the channel that will contain the user's data.

Remembering that the communication link is comprised of

$$\Gamma \text{ bits/unit time} = \Phi \text{ channels/unit time} * \beta \text{ bits/channel}$$

and that while $\Gamma$ is fixed, $\Phi$ and $\beta$ are configurable, not only for the fundamental user, but potentially for other users. If a new user were requesting access after the fundamental user and it is advantageous to the new user or users and not detrimental to the other existing users, the channel size could be reconfigured.

Using the combination of the frequency of transmission of the user requesting to be the fundamental, the amount of data being transmitted per unit time, and the configurable channel size and number of channels, it is possible to adjust the communication link to better support the user's transmission frequency.

For example, set $\Gamma$, the link transmission frequency, to be equal to 10,000 bit per second. The channel can be pre-configured to have $\beta$, the channel size, equal to 20 bits per channel, and the number of channels per second $\Phi$ is 500. There is a new channel transmitted every 2 ms.

**User A** has requested access to the communication link as the fundamental user. User A transmits its data every 40 ms.

The communication link is able to transmit 400 bits every 40 ms.

If **User A** is transmitting data that is 25 bits in length, then there can be 16 channels that will constitute a frame in the link. The size of the channel can be resized from 20 bits in length to 25 bits in length to accommodate the data being transmitted by **User A**. While the link rate $\Gamma$ has remained constant, $\beta$ has changed to 25 bits per channel and $\Phi$ is now 400 channels per second.

It is also a possibility that that the channel size could be set at 40 bits in length. The time between transmissions by **User A** is still 40 ms, as it must be to accommodate the SD user. The number of bits that can be transmitted by the link in that time will also remain the same, still at 400 bits. What has changed is the number of channels that exist between transmissions by **User A**. In the original scenario, there were 16 channels. By increasing the size of the channel, the number of channels per second has decreased, but the location of the **User A's** data in the link has remained the same, which is required for the SD link. These parameter options can be used to generate the constraints for the future optimization of the link.

### 4.1.5. Allowed delay

The fifth parameter of the octuple is the non-fixed delay that can be tolerated. This is represented by **δ**. For non-SD users this parameter could be blank because the data being sent are usually not time-sensitive.

The channel that defines the beginning of the frame is occupied by the fundamental user and will have a zero phase-shift. Its location will be managed by the portion of the admission control software that tracks which frame is allocated to a particular user.

For both classes of users, Synchronous Dependent and non-Synchronous Dependent, having a fundamental user that allows delay and jitter is acceptable. The fundamental user is used as the frame delimiter and since the delimiter is a logical channel marker managed by the method of admission determination and not a physical channel marker, shifting the data forward or data will not change the location of the frame delimiter.

As long as the SD user allows some delay in the transmission of the data, the delay is acceptable. For the non-SD user, the delay is less problematic due to the lack of time restrictions associated with non-SD user transmissions.

### 4.1.6. Allowed jitter

The sixth parameter is the delay variation or jitter, represented by **j**. The jitter for SD users can be zero or some other value; for non-SD users this term would be blank, indicating there is no preference as to the delay variation for this user. With respect to the final parameter discussed below, it is possible that jitter will be induced by the placement of the data on the link, and then returning the data to its original channel when the channel became available again. This situation would occur when the precise frame required by User A is allocated to User B by the CAC. If this occurs, User A will be shifted to the left or the right and then shifted back, inducing jitter into the transmission.

Allowing jitter for the fundamental user does not impact the logical framing structure that is created by the fundamental user, whether the user is SD or non-SD. The actual placement determination will still be tracking the location of the frames and the location of the users in the frames.

### 4.1.7. Maximum burst traffic

The seventh parameter associated with a users request to be admitted to the SD network is the amount of burst traffic the user may be requesting to send, represented by **B**. For the SD users this parameter should be 0, as the periodic nature of the SD data should indicate no burstable traffic. For the non-SD user sending non-periodic data, this parameter would indicate how much traffic could be sent at one time, within the limits of the maximum transmission allowed by parameter $\boldsymbol{\alpha}$.

A user that has bursty data transmissions can be admitted. Again, the fundamental user is used to mark the beginning of the frames and need not necessarily occupy the channel designated for use by the fundamental user. However, if a user is accepted as the fundamental and the service level agreement for this user requires that an allowance for the bursty traffic be made, this will impact the use of other users.

### 4.1.8. Time stamp

The final parameter is an general time stamp of transmission relative to the real-time clock. For the SD user, this would be of the form hh.mm.ss.hs.ts where hh is the hour, mm is the minutes, ss is the seconds, hs is the hundredths of seconds, and ts is ten thousandths of a second. This is relevant only for the SD user with strict timing requirements as to when a frame must be sent. In most cases, even for SD users, it is sufficient that a frame is reserved for the transmission of the SD data, and as long as the data has arrived at the input node, then the transmission can occur on schedule.

The impact of having a user with the time stamp requirement as the fundamental user is to limit the movement of the user's transmission from the assigned channel to another channel.

## 4.2 THE METHOD OF DETERMINING ADMISSION FOR THE FUNDAMENTAL USER

The method to determine the fundamental user may have to choose between multiple users attempting to access the link at the same time in order to become the fundamental user. One method to compare the users is to assign a reward to each characteristic of the octuple, and the user with the highest reward total can be designated as the fundamental. The term reward is used here due to the finite state Markov process methodology which is the solution method chosen. In reality, these rewards are the costs to the user. These costs may already be established in which case the application is simply an analysis based on current operations, or the cost (reward) could be a parameter used by the operators of the link to establish pricing based on the expected users for the link, e.g., the probabilities of receiving requests from users of various types. The values are subjective at this point and can be based on the prevalence of a particular type of traffic that is likely to exist on the communication link. The ability to formulate this problem for the implementer to choose among alternatives based on the current costs is considered a major contribution of this dissertation.

For User A, the first user requesting to be the fundamental, the octuple may have the following configuration, although the values are for example only:

**$U_A$ = (*P*, c, 20, 64, .2ms, .2ms, 0, 0)**

This would be interpreted as a continuous periodic user with 20 data transmissions per second (per unit time) of size 64 bits that allows for a delay of .2 ms and a jitter of .2 ms, having zero bursts of data and no specific time requests. Channels are set at 64 bits in length, based on the user parameters. Channel size could be larger or smaller, but in this case is set at the size of the transmitted data. For the purposes of this example, the frame size is set at 64 channels, including **User A**. With 20 transmissions per second, 64 bits per transmission (channel length), and 64 channels per frame, there are 81,920 bits per second.

User B, the second user to request admission as the fundamental, might have an octuple:

**$U_B$ = (*P*, c, 32, 64, .2ms, .2ms, 0, 0)**

User B is transmitting 64 bits of periodic data at a frequency of 32 transmissions per second. At the same link rate of 81,920 bits per second, this equates to 40 channels per frame.

If a cost (reward) is associated with the characteristics of the users, an example comparison would be as shown in Table 4.1:

**Table 4.1. User Costs (Rewards) Associated with Transmission Characteristics**

| Characteristic | User A | User A Rewards | User B | User B Rewards |
|---|---|---|---|---|
| Periodic | Yes | 10 | Yes | 10 |
| Continuous | Yes | 10 | Yes | 10 |
| Transmission Rate | 20 | 20 | 32 | 5 |
| Channel Size | 64 | 10 | 64 | 10 |
| Delay | .2 ms | 7 | .2 ms | 7 |
| Jitter | .2 ms | 8 | .2 ms | 8 |
| Burst | 0 | 10 | 0 | 10 |
| Time Stamp | 0 | 10 | 0 | 10 |
| Total |  | 85 |  | 70 |

The only difference between the totals associated with User A and User B is related to the transmission frequency of the users. The transmission frequency of User A forms frames 64 channels in length. The transmission frequency of User B forms frames 40 channels in length. Without *a priori* knowledge of the transmission characteristics of other users of the link, User A is rewarded more for having more multiples of the transmission frequency that are able to co-exist without having the need to induce jitter and delay.

What this type of system does do is enable rules to be written that promote one user over another based on the operating environment of the link.

## 4.3 THE METHODOLOGY FOR USERS AFTER THE FUNDAMENTAL

As in the method for the fundamental user, the application of the method of analysis for subsequent users after the fundamental will utilize the same octuple of user characteristics as the fundamental, repeated below:

$[\mathbf{U_i}] = (\boldsymbol{P\ or\ non\text{-}P}, \boldsymbol{c}, \boldsymbol{\rho}, \boldsymbol{\alpha}, \boldsymbol{\delta}, \boldsymbol{j}, \boldsymbol{B}, \boldsymbol{hh.mm.ss.hs.ts})$

- Periodic or non-periodic transmissions
- Continuous or finite transmissions
- Transmission frequency
- Amount of data per unit time
- Allowed delay
- Allowed jitter
- Maximum burst traffic
- Time stamp

The characteristics are a description of the services being requested by the user as in traditional communication pricing, and the admission of the user indicates that the communication link can provide the requested service level to the end user.

The characteristics can be classified into two sub-types:

- Those characteristics that directly relate to the type of service requested (periodic/non-periodic, , transmission frequency, continuous/finite, delay/no delay, jitter/no jitter, time stamp)
- Those characteristics that deal with the amount of data being transmitted per frame (transmission frequency, amount of data per channel, maximum burst traffic). The latter will be discussed further in the next section.

The user characteristics that relate directly to the level of service requested can be used to construct a set of users that incorporate these characteristics. The user types are shown in Table 4.2:

It is important to note that the classification of types chosen is to be able to group users where the characteristics are non-conflicting providing a simple set of blanks to be filled in for admission. As such, the groupings of these user types will form states of the link which will allow users with non-conflicting requirements to be included in the same state thus reducing the necessary testing (analysis) to determine the effect of such a user being admitted.

From the list of potential users, where each state includes the compatible user community, a state diagram can be constructed to show the inter-relationship of the user types. The purpose of the state diagram is to provide the status of the link ***E***, prior to and following the admittance of a user ***x*** **(*x* = A, B, C, E, F, A', B', C', E', or F')** to ***E***. The two states of the link provide the necessary transition that will occur once the candidate user is admitted to the link. The method of analyzing user admission to the link is described through the link indicating changes of state.

**Table 4.2. User Types**

| User Type | User Characteristics |
|---|---|
| A | Synchronous Dependent<br>Continuous<br>Multiple of Fundamental<br>Zero Delay and Zero Jitter |
| B | Synchronous Dependent<br>Continuous<br>Multiple of Fundamental<br>Delay and Jitter Allowed |
| C | Synchronous Dependent<br>Continuous<br>Non-Multiple of Fundamental<br>Zero Delay and Zero Jitter |
| E | Synchronous Dependent<br>Continuous<br>Non-Multiple of Fundamental<br>Delay and Jitter Allowed |
| F | Non- Synchronous Dependent<br>Continuous |
| A’ | Synchronous Dependent<br>Finite<br>Multiple of Fundamental<br>Zero Delay and Zero Jitter |
| B’ | Synchronous Dependent<br>Finite<br>Multiple of Fundamental<br>Delay and Jitter Allowed |
| C’ | Synchronous Dependent<br>Finite<br>Non-Multiple of Fundamental<br>Zero Delay and Zero Jitter |
| E’ | Synchronous Dependent<br>Finite<br>Non-Multiple of Fundamental<br>Delay and Jitter Allowed |
| F’ | Non- Synchronous Dependent<br>Finite |

An important contribution here is the formulation of the link in terms of a concise state diagram based on the ability to differentiate different users into classes (user types) that can then be associated with disjoint states. This differentiation includes the ability to determine conflicting and non-conflicting users. The entire link operation can now be analyzed as a finite state Markov process taking advantage of the previously formulated analysis and optimization work[41].

The current environment of the link ***E*** is determined by the collection of users that have been accepted to some point in time. The strict timing nature of the Synchronous Dependent user does not permit a general relaxing of the constraints on all users for the good of the current users as has been true with other types of links and networks. Traditionally, small delays on a complicated link are considered to be minor compared to the overall link operation. However, it is the general relaxation of all users that precludes the implementation of systems requiring transmissions of the Synchronous Dependent which this research is to overcome.

The restrictions of SD users that are required for one system may not be compatible with other SD users. Thus, in an SD link, as shown earlier in this dissertation, certain users can not coexist. The groupings of users that can coexist as indicated previously are termed *states*. As users are admitted or complete their transmission interval, the nature of the state may change and consequently the current state of the system may differ from the previous set of conditions. Alternatively, a user leaving the link may only cause a transition from the current state back into the identical state.

These changes represented by users entering or leaving the link are simple state transitions that are represented by arcs that connect states with arrows indicating the directional change.

A major contribution of this dissertation is the ability to characterize users in a format such that there is a consistent dichotomy of user groups facilitating the mathematical description of the transitions and the costs or rewards for making these transitions. In this formulation, it is possible to map the link problem onto a classical form of a state diagram with the ability to optimize the overall link (system) performance.

In the following presentation, the pictorial descriptions of the states with the users that can coexist allows the reader to have a simple formulation of the process of the link behavior and state transitions[42].

The state diagram associated with each transition of user type is shown in Figure 4.1. It is important to note that the identification of the state is given by the dominant user(s) determining the characteristics of that particular state. Thus, state A may contain many user types, but the primary state characteristics are determined by state A. The same is true for the designation of state C where user type C is the dominant user determining the characteristics of state C. One state is simply the null state with no users. The other two states have no dominant user thus they are identified by the set of users primarily characterizing the particular state, e.g., state (B,E,F) and state (A', B', C', E', F').

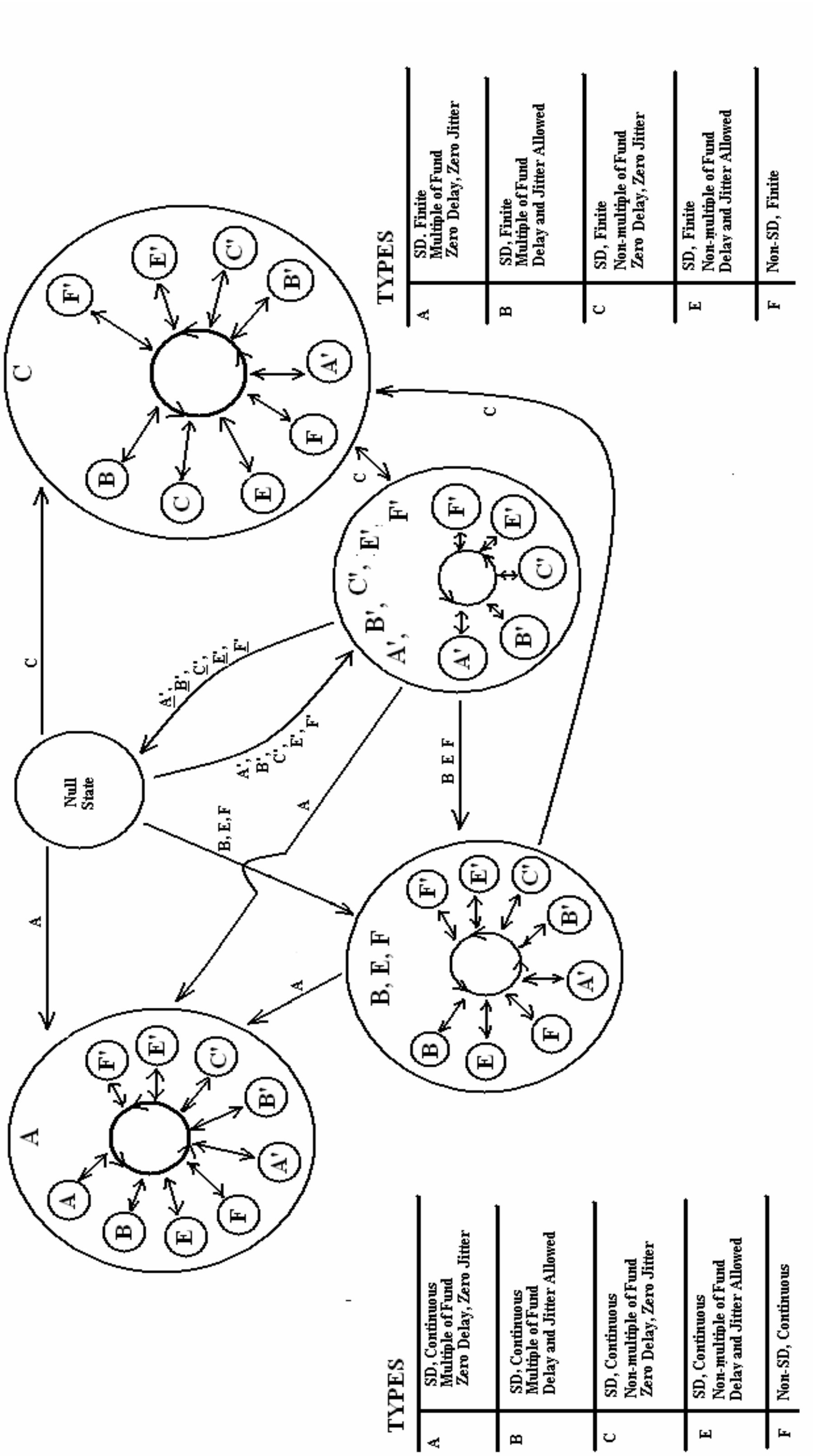


Figure 4.1. State Diagrams of User Types

The state diagram shows that after the fundamental user is chosen from user types **(A, B, C, E, F, A', B', C', E',or F')**, there are four states that can be entered from the empty state, designated **A**, **BEF**, **C**, and **A'B'C'E'F'**.

**A** and **C** are conflicting users and cannot exist in the same state as they are both zero delay and jitter where their transmission frequencies are multiples and non-multiples of the fundamentals respectively. If accepted/admitted they would eventually require the same channel in the frame, i.e., they will share a common zero crossing.

The individual users **B**, **E**, and **F** are in the same grouping designated as state (B, E, F) as they allow jitter and delay and are continuous. This requires all non-SD users to allow jitter and delay.

The users in the last grouping, **A', B',C',E',F'** are all finite and are included in state (A', B', C', E', F'). **A'** and **C'** can co-exist here, as long as the transmission duration is short enough so as to not interfere with another user. The grouping **A'**, **B'**, **C'**, **E'**, **F' ,** state (A', B', C', E', F'), is the return to the zero (empty) user state after termination of all finite user transmissions.

A type **A** or **C** user that is admitted after the fundamental is chosen from any state other than **A** or **C** will transition to the respective **A** or **C** trapping state. From **A** or **C**, all other users are acceptable, other than **A** from **C** or **C** from **A**. States **A** and **C** are trapping states, in that once they are entered by admitting an **A** or **C** user respectively, there is no exit to any of the other non-empty states.

A type **B, E, F** or **A', B', C', E', F'** user that is admitted following the selection of the fundamental will enter the respective state and remain there until the admission of a type **A** or **C** user, at which point a transition occurs to the corresponding trapping state.

There is a probability associated with the each transition from the current state to the next state based on previous data or an expected user distribution. One example set of probabilities for each transition is shown in Figures 4.2 and 4.3 for the purpose of illustration.

In general, these probabilities will be known or determined by the particular operating facility and the community of users. The method to initialize or update the actual probabilities would consist of observing the data transmissions over a period of time. In the initial establishment of the system with no experience for observation, the user would rely on surveys and/or focus groups for the initial probabilities which can be continuously updated between any two transmissions according to the current formulation. Such a methodology allows for adaptation of the link to the current market trends and demands. The *a priori* or operational observations would be based on the octuple presented earlier:

$$[\ U_i\ ] = (P \text{ or non-}P,\ c,\ \rho,\ \alpha,\ \delta,\ j,\ B,\ hh.mm.ss.hs.ts)$$

From the observed data a set of probabilities could be constructed that would be the basis for the analysis as discussed above. Once the initial set of probabilities is constructed, real time monitoring would allow the probabilities to be modified if there were a significant shift in the types of users that were utilizing the link.

The probability of any user requesting admission to the link will be governed by past experience, market research or an estimated set based on the need as perceived by experts in any particular application area.

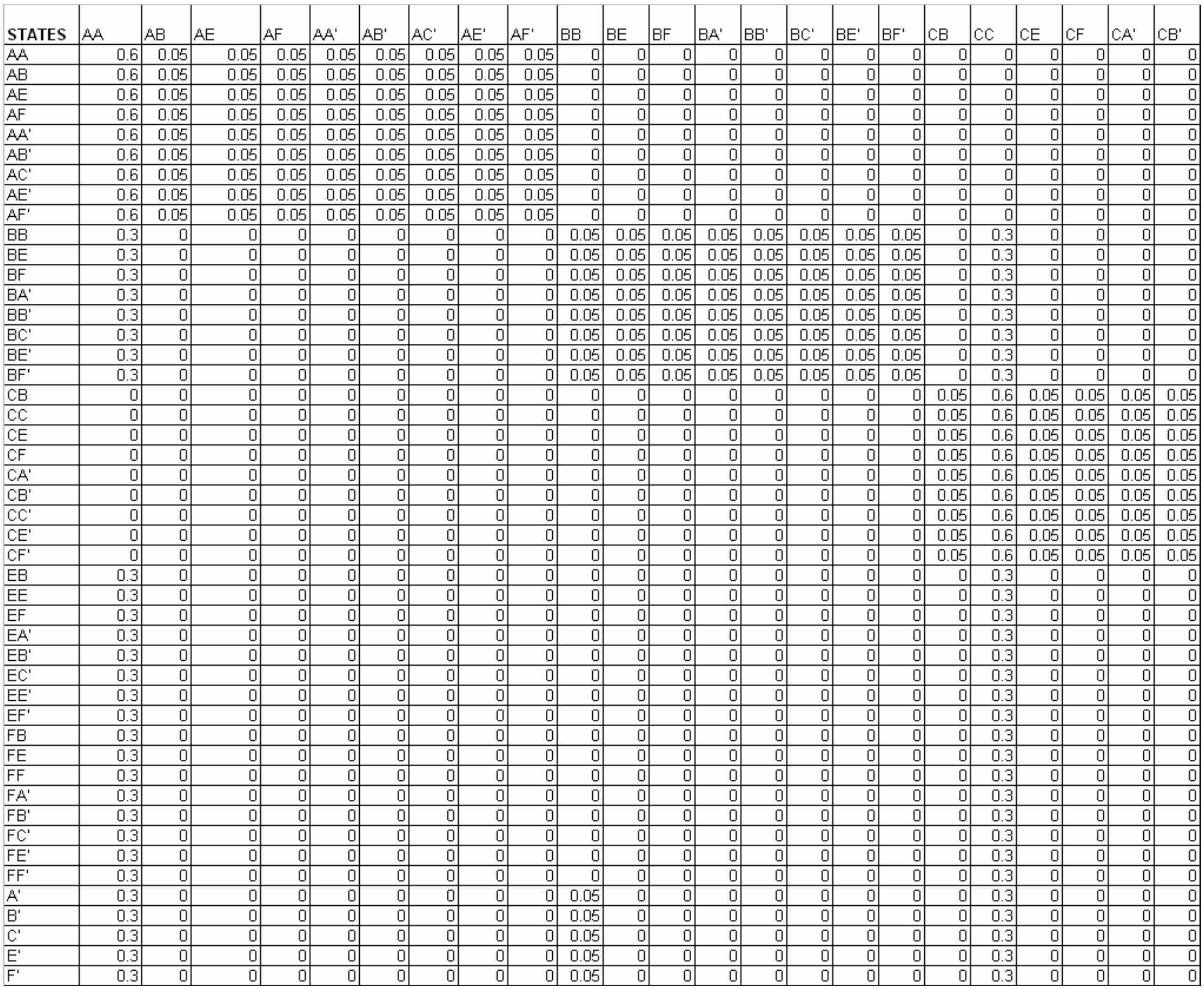
The entire process will be initiated by the first accepted user. Obviously, if that first user is type A or type C, the basic behavior of the link will be determined from that point in time.

However, within either of the two resulting states as well as the initial transition into some initial state, the subsequent states will be determined by the probability of a user requesting admission and the acceptance of the user which can not occur without permission. Thus, it is possible to control the environment of the link by the admission method of analysis and any subsequent or policy formulated by the person (or system) managing the link.

Given any state, the transition is then determined by the probability that a user will request admission. The behavior from that point on is determined by the admission method of analysis which is only important in considering user classes which can not coexist in the same state. Thus, the state diagram and any attendant mathematical basis will constitute a method of analysis which will be used to determine the value in accepting any appearing user. The transition from one state to another is therefore the probability of the user type appearing and the decision to admit the user being positive.

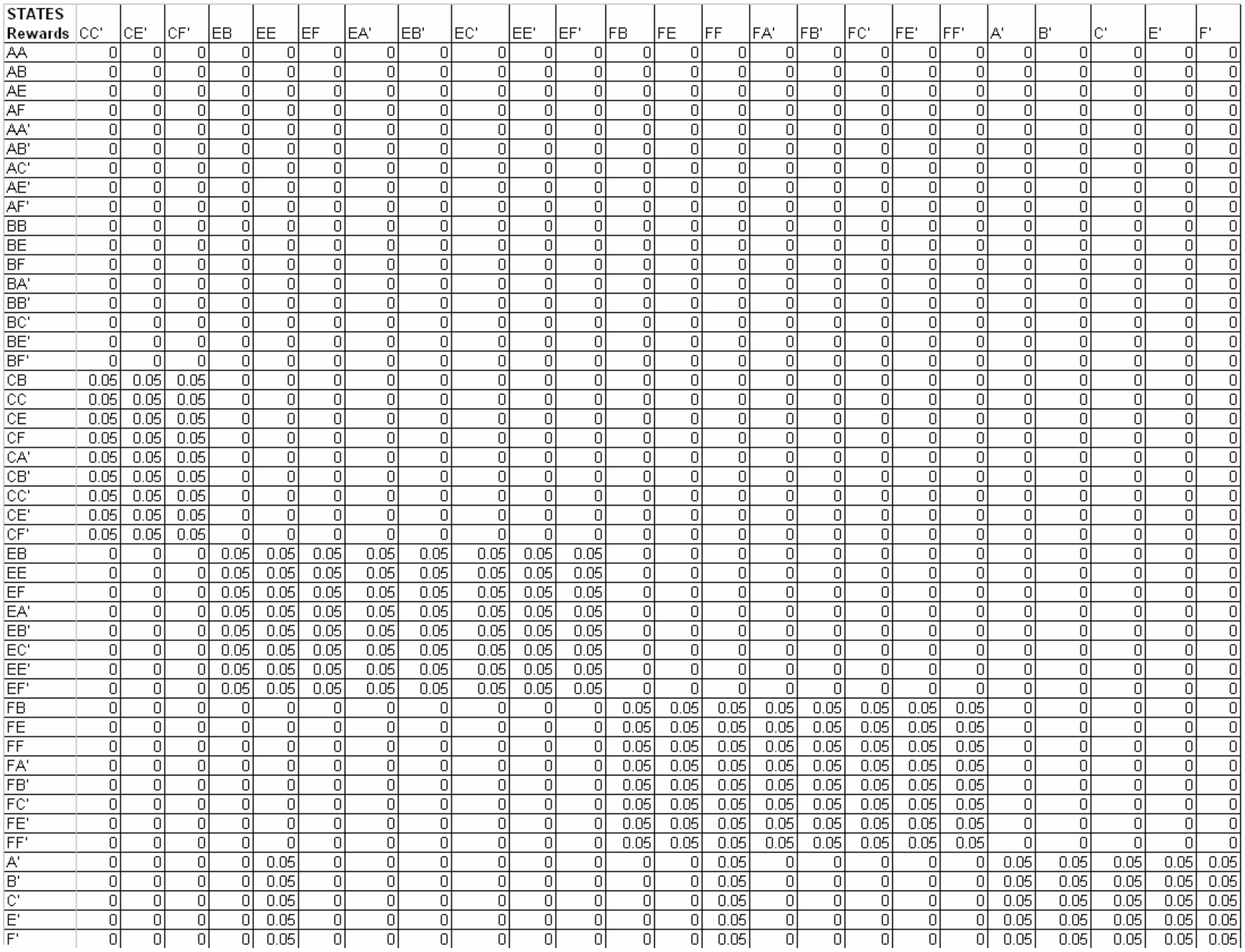
The transition from state to state is thus dependent on the probability of the user appearing and the acceptance. For a current state, $i$, the user type will be incorporated into the link by the state transition that will be caused by this admission. The link will transition to state $j$, where $i = j$, is possible for a user of the same or compatible type. This probability will be noted as, $p_{ij}$, which will be characterized by an $n$ by $n$ square matrix for a link environment consisting of $n$ states. The resulting matrix of probabilities will fully describe the possible state transitions of the link with the given probabilities assuming the appearing user is admitted[43]. Note that the state diagram contains only five states including the null state. In order to properly account for the transitions of all user types, the 5 states of Figure 4.1 can be disaggregated to 47 states comprising all the required user identities to properly affix both probabilities and rewards. There is no loss to generality in this aggregation or disaggregation other than the ability to simply view the aggregated states on a single diagram. The individual user states aggregated into a given state are included within the states illustrated in Figure 4.1.

In general, the aggregation patterns can be observed in the square blocks of Figure 4.1. However, no advantage will be taken by this block form appearance[44].



| STATES | AA | AB | AE | AF | AA' | AB' | AC' | AE' | AF' | BB | BE | BF | BA' | BB' | BC' | BE' | BF' | CB | CC | CE | CF | CA' | CB' |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AB | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AE | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AF | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AA' | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AB' | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AC' | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AE' | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AF' | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BB | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| BE | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| BF | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| BA' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| BB' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| BC' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| BE' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| BF' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| CB | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 |
| CC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 |
| CE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 |
| CF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 |
| CA' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 |
| CB' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 |
| CC' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 |
| CE' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 |
| CF' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.6 | 0.05 | 0.05 | 0.05 | 0.05 |
| EB | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| EE | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| EF | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| EA' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| EB' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| EC' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| EE' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| EF' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| FB | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| FE | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| FF | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| FA' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| FB' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| FC' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| FE' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| FF' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| A' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| B' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| C' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| E' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |
| F' | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 |

**Figure 4. 2 Matrix of the List of Probabilities (Part A)**



| **STATES Rewards** | CC' | CE' | CF' | EB | EE | EF | EA' | EB' | EC' | EE' | EF' | FB | FE | FF | FA' | FB' | FC' | FE' | FF' | A' | B' | C' | E' | F' |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AB | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AA' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AB' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AC' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AE' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AF' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BB | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BA' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BB' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BC' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BE' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BF' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CB | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CC | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CE | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CF | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CA' | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CB' | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CC' | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CE' | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CF' | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EB | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EE | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EF | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EA' | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EB' | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EC' | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EE' | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EF' | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| FB | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 |
| FE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 |
| FF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 |
| FA' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 |
| FB' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 |
| FC' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 |
| FE' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 |
| FF' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 |
| A' | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| B' | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| C' | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| E' | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| F' | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |

**Figure 4. 3 Matrix of the List of Probabilities (Part B)**

## 4.4 REWARDS

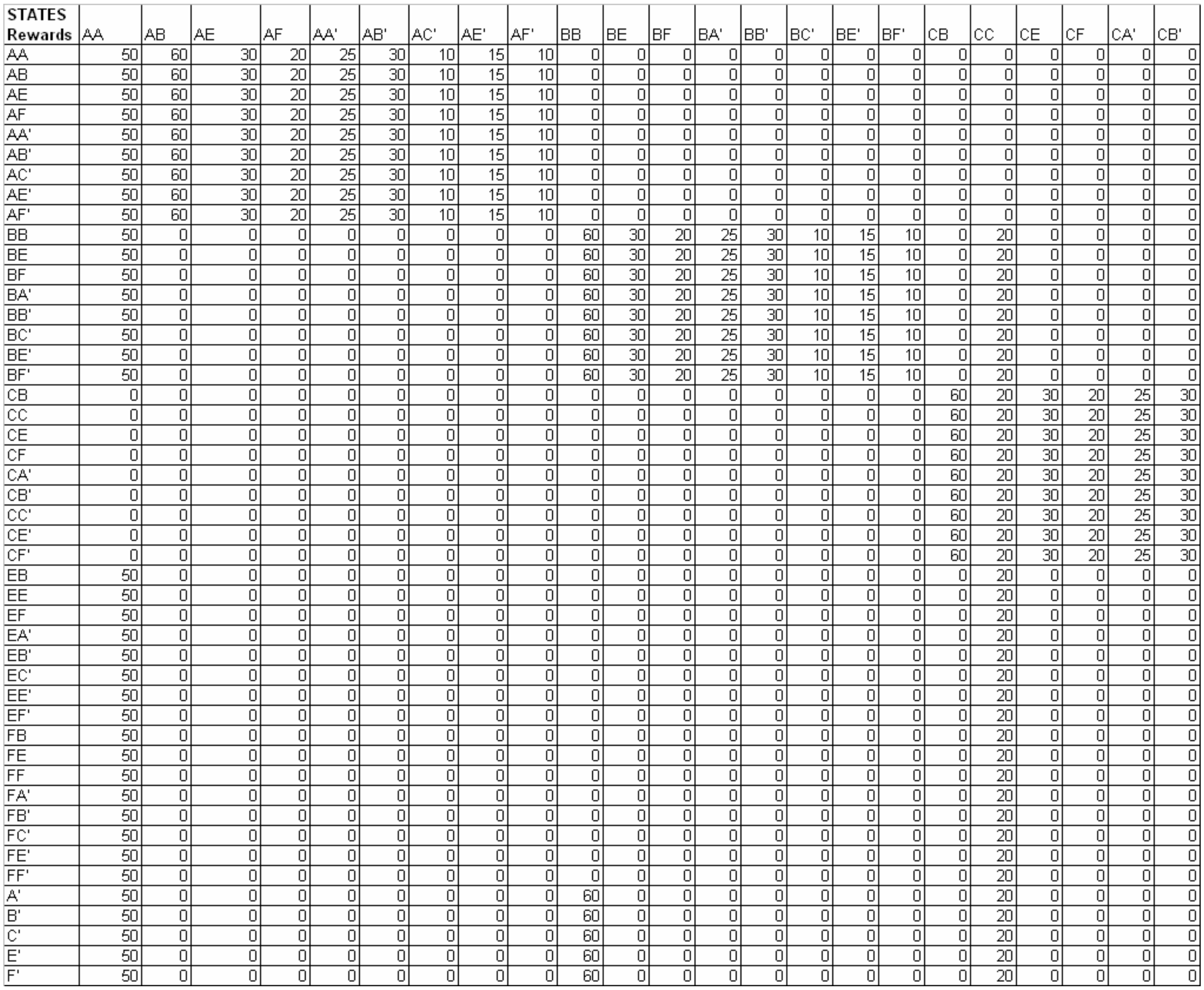
A usage charge based on the octuple of each user can now be established for each user and user type. The usage charge will be termed a reward in the sense of a finite state Markov process. A reward can also be associated with each change of state. This factor is why it is necessary mathematically to account for all of the user types so as to provide flexibility to the operator of the link to properly price each user transition and to predict subsequent behavior. The rewards at this point are arbitrary and are used as part of a methodology to demonstrate the means to admit one type of user as opposed to another type of user. Or to state it another way, to evaluate the alternatives of admitting or not admitting the user for the transition from one state to an optimal state as opposed to a non-optimal state. The example rewards are shown in Table 4.2. Note there is a one to one correspondence between the positions of the rewards and the probabilities in the two matrices.

**Table 4.3. User Types with Rewards**

| User Type | User Characteristics | Rewards |
|---|---|---|
| A | Synchronous Dependent<br>Continuous<br>Multiple of Fundamental<br>Zero Delay and Zero Jitter | 50 |
| B | Synchronous Dependent<br>Continuous<br>Multiple of Fundamental<br>Delay and Jitter Allowed | 60 |
| C | Synchronous Dependent<br>Continuous<br>Non-Multiple of Fundamental<br>Zero Delay and Zero Jitter | 20 |
| E | Synchronous Dependent<br>Continuous<br>Non-Multiple of Fundamental<br>Delay and Jitter Allowed | 30 |
| F | Non- Synchronous Dependent<br>Continuous | 20 |
| A’ | Synchronous Dependent<br>Finite<br>Multiple of Fundamental<br>Zero Delay and Zero Jitter | 25 |
| B’ | Synchronous Dependent<br>Finite<br>Multiple of Fundamental<br>Delay and Jitter Allowed | 30 |
| C’ | Synchronous Dependent<br>FiniteNon-Multiple of Fundamental<br>Zero Delay and Zero Jitter | 10 |
| E’ | Synchronous Dependent<br>FiniteNon-Multiple of Fundamental<br>Delay and Jitter Allowed | 15 |
| F’ | Non- Synchronous Dependent<br>Finite | 10 |

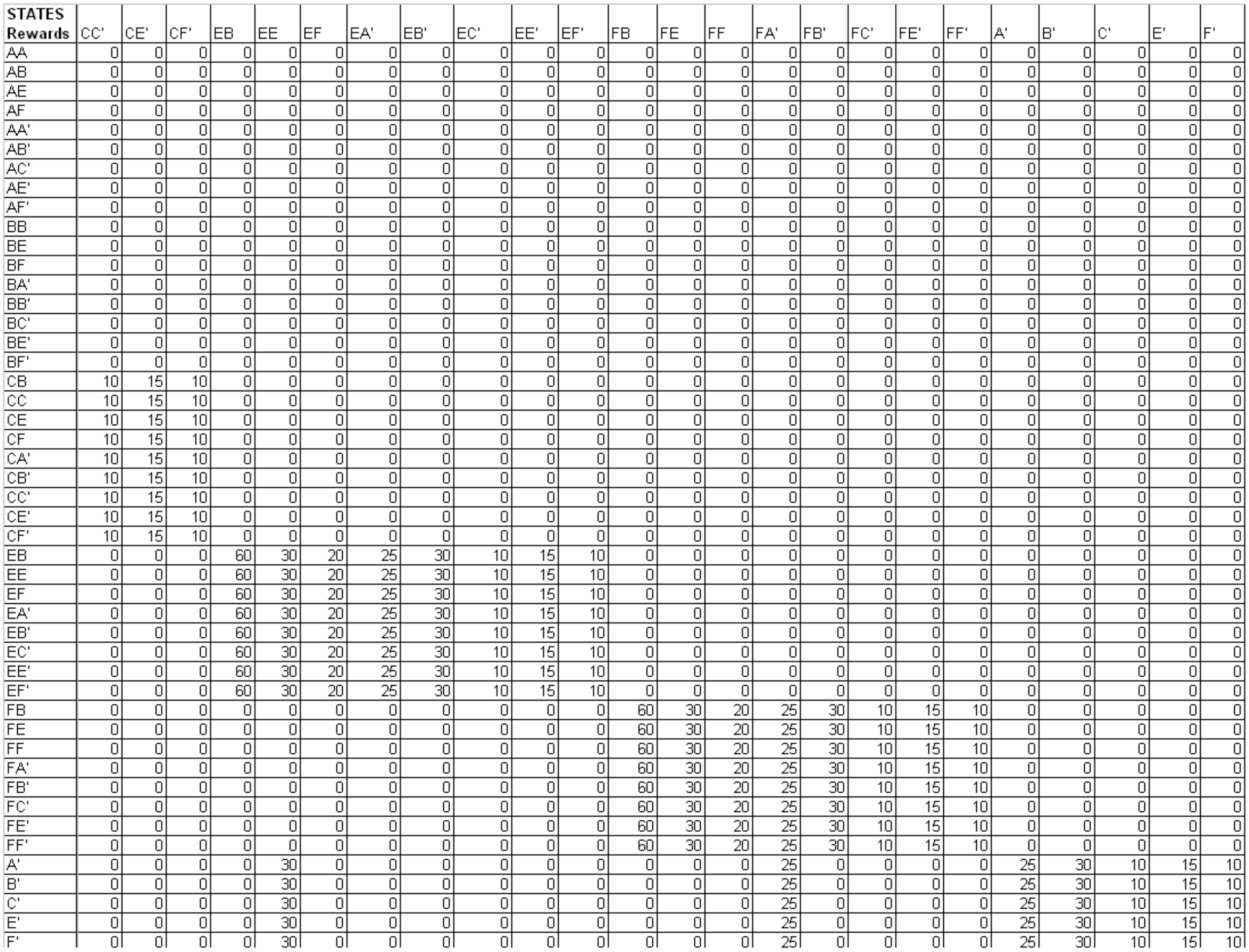
The matrix for the rewards relative to transitioning from one state to another is shown as Figures 4.4 and 4.5. The chosen values are for demonstration purposes only, but they illustrate the incentive that has been provided to allow the manager of the link to optimize the performance based on anticipated probabilities and a reward structure to reflect both the non-recurring and recurring costs to operate the link.

The example rewards were based on the user's characteristics to tolerate jitter and delay first, as the flexibility to move the user's data from channel to channel will potentially allow more users access to the link. The second criterion for rewards was whether the user requesting access to the link had a transmission frequency that was a multiple of the fundamental frequency. A user with a transmission frequency that is a multiple of the fundamental will not induce jitter in like users. The actual rewards determined by the link operator may be based on these criteria or some other, dependent on the nature of the data transmissions. In any application, the goals of the particular provider are the governing aspect of the methodology to establish the rewards. This is a specific advantage of this formulation in that it provides the "hooks" for the system operator to optimize the link instantaneously or over time.



| STATES Rewards | AA | AB | AE | AF | AA' | AB' | AC' | AE' | AF' | BB | BE | BF | BA' | BB' | BC' | BE' | BF' | CB | CC | CE | CF | CA' | CB' |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA | 50 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AB | 50 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AE | 50 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AF | 50 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AA' | 50 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AB' | 50 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AC' | 50 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AE' | 50 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AF' | 50 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BB | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 20 | 0 | 0 | 0 | 0 |
| BE | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 20 | 0 | 0 | 0 | 0 |
| BF | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 20 | 0 | 0 | 0 | 0 |
| BA' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 20 | 0 | 0 | 0 | 0 |
| BB' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 20 | 0 | 0 | 0 | 0 |
| BC' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 20 | 0 | 0 | 0 | 0 |
| BE' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 20 | 0 | 0 | 0 | 0 |
| BF' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 20 | 0 | 0 | 0 | 0 |
| CB | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 20 | 30 | 20 | 25 | 30 |
| CC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 20 | 30 | 20 | 25 | 30 |
| CE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 20 | 30 | 20 | 25 | 30 |
| CF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 20 | 30 | 20 | 25 | 30 |
| CA' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 20 | 30 | 20 | 25 | 30 |
| CB' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 20 | 30 | 20 | 25 | 30 |
| CC' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 20 | 30 | 20 | 25 | 30 |
| CE' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 20 | 30 | 20 | 25 | 30 |
| CF' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 20 | 30 | 20 | 25 | 30 |
| EB | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| EE | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| EF | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| EA' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| EB' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| EC' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| EE' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| EF' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| FB | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| FE | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| FF | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| FA' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| FB' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| FC' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| FE' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| FF' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| A' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| B' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| C' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| E' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |
| F' | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 0 | 0 | 0 | 0 |

**Figure 4. 4  Matrix of the Rewards (Part A)**



| STATES Rewards | CC' | CE' | CF' | EB | EE | EF | EA' | EB' | EC' | EE' | EF' | FB | FE | FF | FA' | FB' | FC' | FE' | FF' | A' | B' | C' | E' | F' |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AB | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AA' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AB' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AC' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AE' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| AF' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BB | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BA' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BB' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BC' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BE' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BF' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CB | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CC | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CE | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CF | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CA' | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CB' | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CC' | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CE' | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CF' | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EB | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EE | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EF | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EA' | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EB' | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EC' | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EE' | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| EF' | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| FB | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 |
| FE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 |
| FF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 |
| FA' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 |
| FB' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 |
| FC' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 |
| FE' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 |
| FF' | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 60 | 30 | 20 | 25 | 30 | 10 | 15 | 10 | 0 | 0 | 0 | 0 | 0 |
| A' | 0 | 0 | 0 | 0 | 30 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 25 | 30 | 10 | 15 | 10 |
| B' | 0 | 0 | 0 | 0 | 30 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 25 | 30 | 10 | 15 | 10 |
| C' | 0 | 0 | 0 | 0 | 30 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 25 | 30 | 10 | 15 | 10 |
| E' | 0 | 0 | 0 | 0 | 30 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 25 | 30 | 10 | 15 | 10 |
| F' | 0 | 0 | 0 | 0 | 30 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 0 | 25 | 30 | 10 | 15 | 10 |

**Figure 4. 5 Matrix of the Rewards (Part B)**

With the probabilities of changing states, **P**, and the rewards, **R**, it is possible to calculate a gain which indicates the expected future value based on alternative policies and decisions[45].

The **P** and **R** matrices are to be combined with the notation, **P**⊗**R** , where the ⊗ operator is defined by the following relationship:

$$\mathbf{P}\otimes\mathbf{R} = \mathbf{col}\ [p_{i,1}*r_{i,1} + p_{i,2}*r_{i,2} + \ldots + p_{i,n}*r_{i,n}];\ i = 1, 2, \ldots , n$$

The result is then combined with the initial state vector, $\boldsymbol{\pi}(\mathbf{0})$, to yield the expected value for the next state transition[46],

$$\mathbf{q} = \boldsymbol{\pi}(\mathbf{0})\ \mathbf{P} \otimes \mathbf{R}$$

where $\boldsymbol{\pi}(\mathbf{0})$ can be any point at which a decision is to be made, or in the current problem, any point at which a user is being evaluated for admission to the link ***E***.

The time scale of the problem involved indicates that we are looking at the steady state analysis of the behavior of the link. For any such Markov process, the vector of absolute state probabilities, $\boldsymbol{\pi}$, yields the probability of being in any state over all future time. Based on the expected value of the next transition and over all future time, it is possible to express a gain of the system in terms of $\boldsymbol{\pi}$, $\boldsymbol{\pi}(\mathbf{0})$, $\mathbf{P} \otimes \mathbf{R}$, and **S**, where $\mathbf{S} = \mathbf{col}\ (\boldsymbol{\pi})$ such that each row of **S** is the vector of absolute state probabilities for the system beginning in that particular state, i.e, $\boldsymbol{\pi}_\mathbf{i}$ is associated with (0, 0, ... , i, ...,0, 0)[47].

Thus, the probabilities are given by known or assumed statistics as in this example on the potential user community giving the matrix **P**. The rewards, **R**, are the known or desired charges to be used with the given class of users. With these two sets of data, it is possible to formulate the optimum decision problem for the link operator.

For purpose of example, the matrix, **P**, will be assumed to be given in the matrix of Figure 4.2 and 4.3, and the reward matrix, **R**, will be assumed to be that given in Figure 4.4 and 4.5. The matrix **S** can be obtained by raising the matrix **P** to a power at which the rows stabilize to a constant value[48] based on the fact that the probability matrix, **P**, is stochastic. In the event that the system is *completely ergodic*, independent of the starting state, the rows of **S**, will all be equal.

Otherwise the rows will differ as in the current example because accepting a user **A**, or a user **C**, results in the trapping states **A** and **C** of Figure 4.1, in which case there is no transition from state **A** to state **C**, or alternatively, no transition from state **C** to state **A**.

Given the expected value for the next transition, **P**⊗**R**, it is possible to form an expression for the gain of the system over n transitions[49]:

$$\mathbf{g} = \mathbf{Sq} = \mathbf{S(P \otimes R)}$$

Thus, any $g_i$, of **g** is a function of $p_{ij}$, $r_{ij}$ and the structure of the system. The values of the matrices, **P** and **R**, are to some extent the choice of the system/link management - especially **R** which is equivalent to pricing. The matrix, **P**, is to some extent also a function of **R** in that pricing will affect demand and thus ultimately, **P**. This relationship is an area of application where the research is to be used.

As an example, once a type **C** user is admitted, all type **A** users will be excluded and vice versa. Thus, accepting a type **C** user must by priced sufficiently high in relation to the probability of future type **C** users, p(C).

Thus, given **P** and **R**, it is possible through this research to directly compute the gain (income) of a policy of accepting a particular user or a complete ensemble of users over time.

The application of the gain calculations is applied at the point of making a decision and the actual decision of whether or not to admit a candidate user. Shown in Table 4.4 are the resultant gains for the system:

**Table 4.4. Gains for State Transitions**

| STATES Gain | |
|---|---|
| AA | 40 |
| AB | 40 |
| AE | 40 |
| AF | 40 |
| AA' | 40 |
| AB' | 40 |
| AC' | 40 |
| AE' | 40 |
| AF' | 40 |
| BB | 31 |
| BE | 31 |
| BF | 31 |
| BA' | 31 |
| BB' | 31 |
| BC' | 31 |
| BE' | 31 |
| BF' | 31 |
| CB | 22 |
| CC | 22 |
| CE | 22 |
| CF | 22 |
| CA' | 22 |
| CB' | 22 |
| CC' | 22 |
| CE' | 22 |
| CF' | 22 |
| EB | 31 |
| EE | 31 |
| EF | 31 |
| EA' | 31 |
| EB' | 31 |
| EC' | 31 |
| EE' | 31 |
| EF' | 31 |
| FB | 31 |
| FE | 31 |
| FF | 31 |
| FA' | 31 |
| FB' | 31 |
| FC' | 31 |
| FE' | 31 |
| FF' | 31 |
| A' | 31 |
| B' | 31 |
| C' | 31 |
| E' | 31 |
| F ' | 31 |
| | |

Consider the cost of admitting a type **C** user compared to not admitting any future type **A** user. When the type C user is admitted, whether from the zero (empty) state or from state (**BEF**) or state (**A’B’C’E’F’**), the rewards for admitting any user after user **C** are the same. The lower gain associated with state **C** is based on the **C** type user being a non-multiple of the fundamental, causing delay and jitter. The associated state **A** gain is based on the type **A** user being a multiple of the fundamental, which causes less jitter and delay. Thus, in this example, one would choose a type A user over a type C user.

## 4.5 THE TRANSMISSION FREQUENCY ALLOCATION METHODOLOGY

The user requesting admission to the link could have a maximum of eight parameters that characterize and quantify the reservation needs required by the user, represented by the octuple:

$$[\,U_i\,] = (\boldsymbol{P \text{ or non-}P},\ \boldsymbol{c},\ \boldsymbol{\rho},\ \boldsymbol{\alpha},\ \boldsymbol{\delta},\ \boldsymbol{j},\ \boldsymbol{B},\ \boldsymbol{hh.mm.ss.hs.ts})$$

The components of the octuple that specify the amount of data being transmitted per unit time and at what frequency are $\boldsymbol{\rho}$, the transmission frequency, $\boldsymbol{\alpha}$, amount of data per transmission, and $\boldsymbol{B}$, the amount of burstable data. Supporting the placement of data in the link are the requirements of the user for delay and jitter, $\boldsymbol{\delta}$ and $\boldsymbol{j}$, respectively.

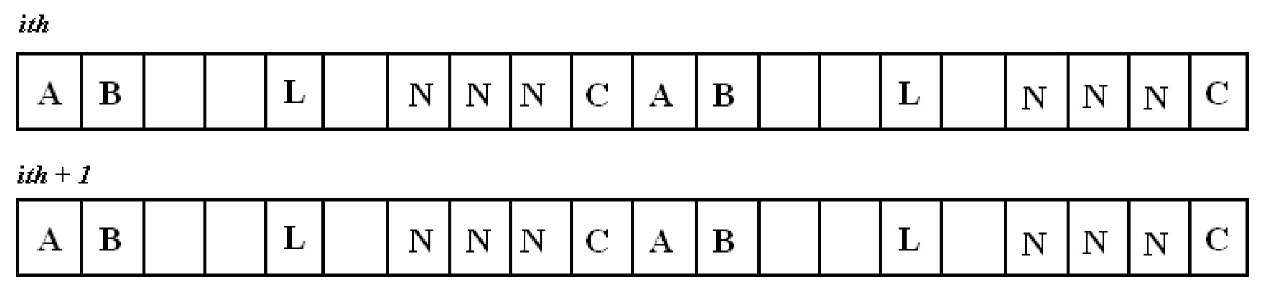
The link $\boldsymbol{E}$, the channels of the link, and likewise the frames of the link have been characterized as a sine wave and phase shift relative to the fundamental frequency which is used as a logical frame delimiter. The equation for a frame of the link is shown below.

$$f(E_i) = + \sum_{j=0}^{n-1} \sin(\omega * t + \varphi_j) \qquad \textbf{for} \quad 0 \le \omega t < 2\pi$$

$$\textbf{and} \quad 0 \le \varphi_i < \pi$$

To determine whether the new user requesting admission to the link can be admitted, a model or series of models of the channels requested by the new user will be built from the information provided by the octuple.

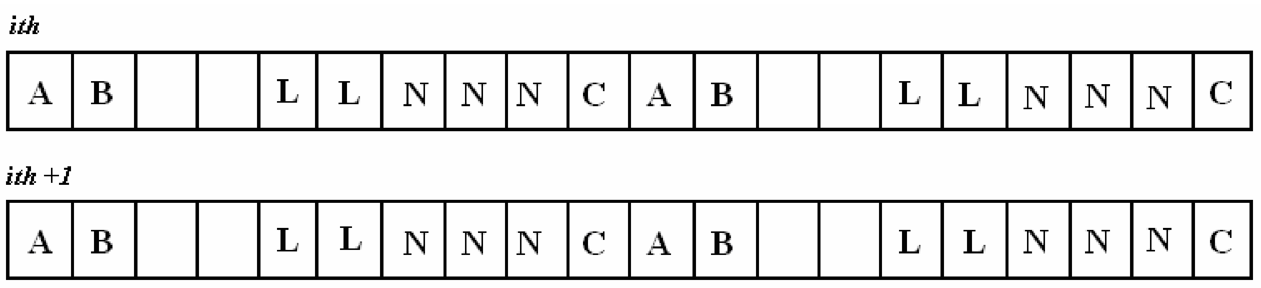
For an SD user, **User L**, the octuple first indicates $\rho$, the frequency of transmission of the user. From the frequency of transmission the number of transmissions per frame is determined. For example, if there are 40 frames per unit time and **User L** is transmitting at 80 transmissions per unit time, there are then two transmissions per frame for **User L**. If the number of channels per frame is a multiple of 2, then **User L's** transmissions can be placed into the frame without disrupting other users, if there are open channels. The representation of this is shown in Figure 4.4, with the number of channels per frame set at 20 and **User A**, **User B**, **User C** and **User N** already occupying the link.



| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *ith* | A | B | | | L | | N | N | N | C | A | B | | | L | | N | N | N | C |
| *ith* + *1* | A | B | | | L | | N | N | N | C | A | B | | | L | | N | N | N | C |

**Figure 4.6. Frames in Link *E* With the Addition of User L**

If **User L** is transmitting more data per transmission than will fit into a single channel, then two (or more) channels per transmission per channel will be used. This is shown in Figure 4.5.



| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *ith* | A | B | | | L | L | N | N | N | C | A | B | | | L | L | N | N | N | C |
| *ith* +*1* | A | B | | | L | L | N | N | N | C | A | B | | | L | L | N | N | N | C |

**Figure 4.7. Frames in Link *E* With the Addition of User L Requiring Two Channel per Transmission**

The equation for the ***ith*** frame prior to the admission of User L would have been

$$f(E_i) = + \sum_{j=x} \sin(\omega_A * t + \varphi_j)$$

$x = 1,2,7,8,9,10,11,12,17,18,19,20$

**for** $0 \leq \omega t < 2\pi$

**and** $0 \leq \varphi_j < \pi$

The equation for **User L** when it requires two channels per transmission would be

$$f(E_L) = + \sum_{j=x} \sin(\omega_A * t + \varphi_j)$$

$x = k, k+1, k+10, k+11$

**for** $0 \leq \omega t < 2\pi$

**and** $0 \leq \varphi_J < \pi$

To determine whether User L can be admitted to the frame and the link in this case, it is matter of examining the phase shifts associated with the ***ith*** frame (the users already accepted on the link), assuming all frames are identical, and searching the empty channels to determine if the necessary channels are available to admit **User L**. The unused channels of the frame are 3, 4, 5, 6, 13, 14, 15,16. There are multiple solutions that fit the requested channel pattern for **User L** that are determined by selecting a value for ***k*** (k = 5, as an example, indicating the phase shift) and solving for the other phase shifts. In this instance, the resultant equation for the ***ith*** frame is

$$f(E_i) = + \sum_{j=x} \sin(\omega * t + \varphi_j)$$

$x = 1,2,5,6,7,8,9,10,11,12,15,16,17,18,19,20$

**for** $0 \leq \omega t < 2\pi$

**and** $0 \leq \varphi_j < \pi$

The example above does not utilize any of jitter or delay information that would be associated with the individual users. Allow the ***ith*** frame to instead be represented by

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *ith* | A | B | G | | H | | N | N | N | C | A | B | | | | | N | N | N | C |
| *ith + 1* | A | B | G | | H | | N | N | N | C | A | B | | | | | N | N | N | C |

**Figure 4.8. Frame in Link *E* Prior to Admission of User L**

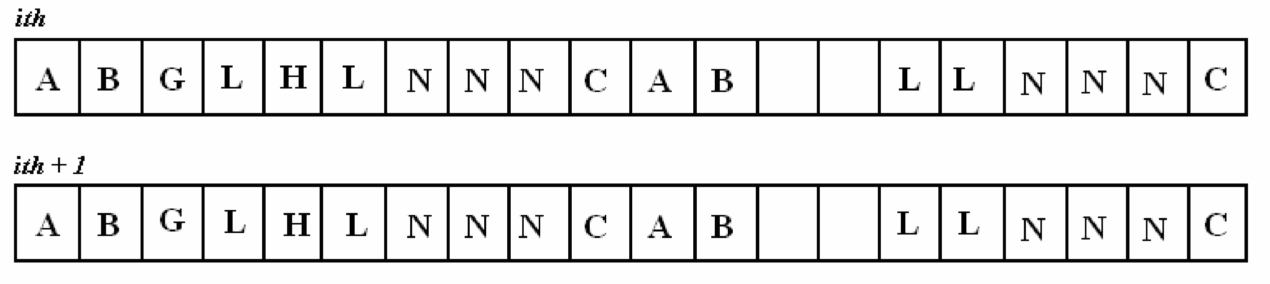
where the phase shift identifier for the link would be:

$x_i = \{1,2,3,5,7,8,9,10,11,12,17,18,19,20\}$.

If **User L** requests access to the link with the same set of requirements for placement except that and allowance is made for delay and jitter where the requirements may be represented by

$x_L = \{ k \pm 1, k+1 \pm 1, k+10 \pm 1, k+11 \pm 1\}$

where the $\pm$ **1** indicates an allowance for the placement of the transmitted data forward or backward in the frame. User L now allows delay for its transmission. Allowing k = 5 again yields the solution shown in Figure 4.7, where the phase shifts are now {4, 6, 15, and 16}. The transmitted data may now be placed in the frame with a possible placement as shown in Figure 4.7



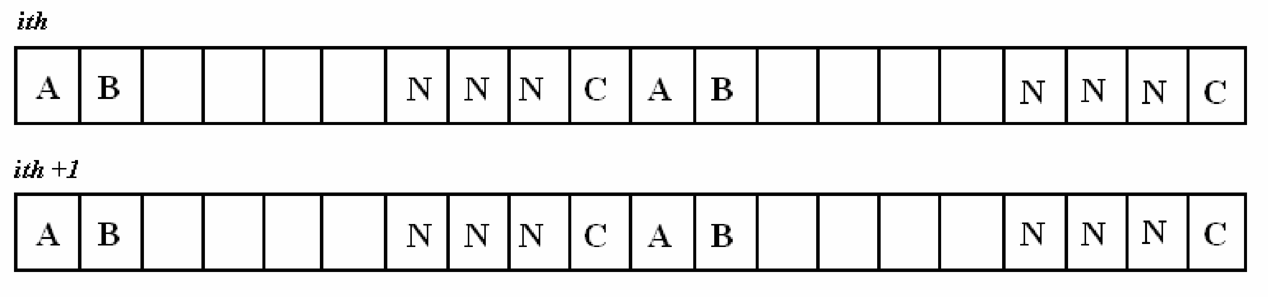
| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *ith* | A | B | G | L | H | L | N | N | N | C | A | B | | | L | L | N | N | N | C |
| *ith + 1* | A | B | G | L | H | L | N | N | N | C | A | B | | | L | L | N | N | N | C |

**Figure 4.9. Frame in Link *E* after Admission of User L With Delay of L**

In this example the delay requirements of **User L** allow the transmission to be delayed such that the data can be inserted into the link. Similarly, if **User H's** requirements allowed delay its transmission could have been delayed to accommodate **User L**.

As in the first example, the placement of the data in the frame requires determining whether there are sufficient channels available by examining the phase shift of the link and the phase shift of the user requesting access.

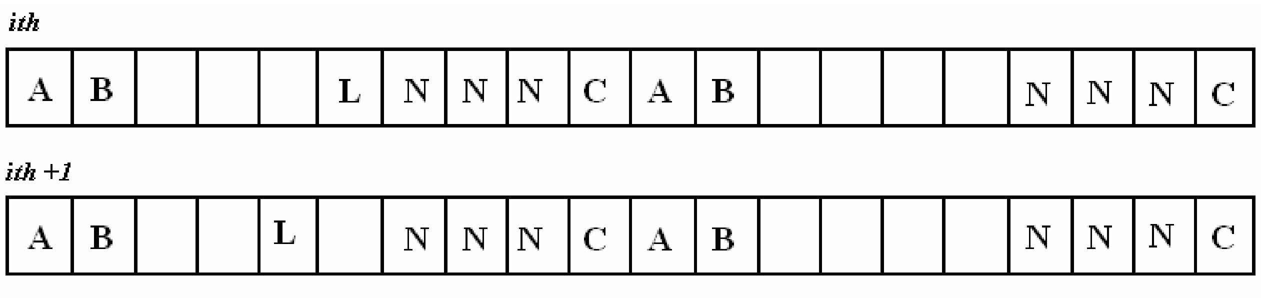
The scenario where the user requesting admission to the link ***E*** is not a multiple of the fundamental frequency requires the examination of all users accessing the link to determine whether the link ***E*** has sufficient resources to admit the new user. If **User L** is not a multiple of the fundamental, the transmission will appear to slide through the frame, disrupting all users. If the users in the link and **User L** do not allow for delay and jitter (shifting the data forward and backward) then **User L** may not be admitted to the link. As an example, where the link has users in the link as shown in Figure 4.8, if the new **User L** has a transmission frequency



| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *ith* | A | B | | | | | N | N | N | C | A | B | | | | | N | N | N | C |
| *ith +1* | A | B | | | | | N | N | N | C | A | B | | | | | N | N | N | C |

**Figure 4.10. Link *E* Prior to Admission of User L with Transmission Frequency slightly Faster Than User A**

that is slightly faster than **User A**, such that **User L** will slide through the successive frames one channel at a time, as was shown in Section 3. The ***ith*** frame and the ***ith* + *1*** frame would appear as in Figure 4.9. In this example, User L requires only one channel for the transmission of its data.



| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *ith* | A | B | | | | L | N | N | N | C | A | B | | | | | N | N | N | C |
| *ith +1* | A | B | | | L | | N | N | N | C | A | B | | | | | N | N | N | C |

**Figure 4.11. Link *E* After the Admission of User L with Transmission Frequency slightly Faster Than User A**

The admission of **User L** will eventually cause the displacement of each user in the frame, which in an environment of SD users may not be acceptable. Before attempting to place the transmitted data into a channel and assigning a phase shift, particularly since the data will not occupy a fixed channel, it should be verified that every user permits delay and jitter. Only after verifying that every user can be delayed, **User L** can be admitted.

The scenarios above indicate that the placement of the data requires:

1.) Determining whether the user requesting access is SD or non-SD.

2.) Determining whether the user requesting access to the link is a multiple of the fundamental, if SD.

3.) Determining the amount of data per transmission is being requested

4.) Determining whether jitter or delay is allowed by the requesting user.

5.) Determining whether there are channels available for the new user.

6.) Determining whether the existing users can be shifted in the frame to accommodate the requesting user.

Step 6 above is the complex, as it requires the monitoring of the jitter and delay of each user. Alternatively, it may be possible to construct a set of flags, indicating the state of the network, which indicate the minimum number of channels that any user can be moved. If a user requesting access to the link requires that some users may have to be shifted ***m*** number of channels to accommodate the new user, and the minimum flag is set to **n, n < m**, it is known the new user will not be granted access.

## 5.0 HALF-DUPLEX AND FULL DULPLEX COMMUNICATION

The communication link ***E*** has so far been characterized as a one-way, half duplex link. As the link may be the communication path between a sampling device and an actuator, a two-way, full duplex communication link may be necessary.

Half duplex communication is typically viewed as a two-way communication between two entities that permits communication in one direction at a time. While **User 1** is communicating (transmitting), **User 2** is listening. **User 2** may then respond to **User 1** over the same communication path but in the reverse direction. Early forms of bus-based Ethernet would fit this description, because the use of Carrier Sense Multiple Access with Collision Detection only allowed one user to transmit while the others listened, although this typically involves the capability of more than one user listening.

Conversely, full duplex communication allows the entities to transmit and receive simultaneously. The most common example of this form of communication is a phone conversation. An end-to-end link exists that allows both users to talk and listen at the same time. In the representation of a phone conversation shown in Figure 5.1, two users are shown saying “Hello” at the same time. For the purpose of this illustration, it will be assumed the conversation is over a digital link as opposed to an analog two-wire telephone system.

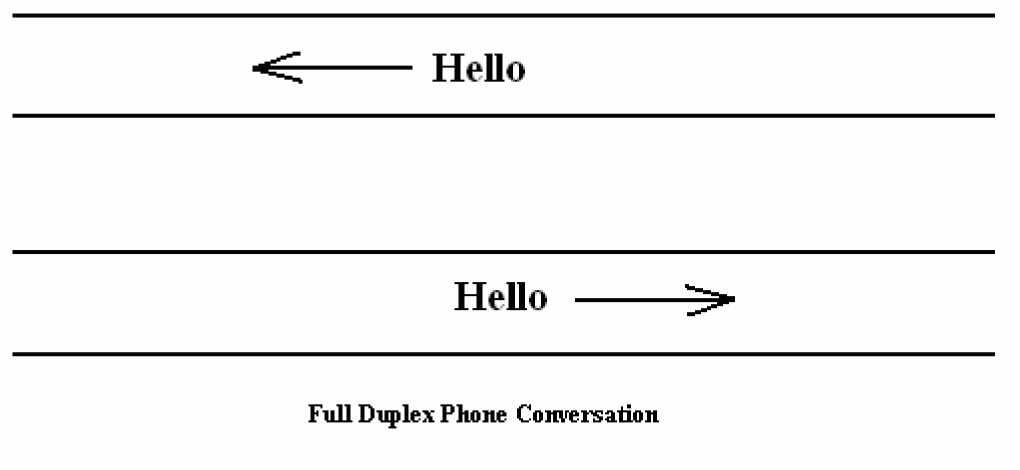


**Figure 5.1. Full Duplex Phone Conversation**

The significance of the communication shown in Figure 5.1 is that both users are able to transmit data at the same time on separate links. What is also significant is that the messages appear to occur at the same time. A more likely communication scenario is the one shown in Figure 5.2, where the users have the capability to transmit simultaneously but the response to the original transmission is delayed in the other direction relative to receiving and processing the initial query.

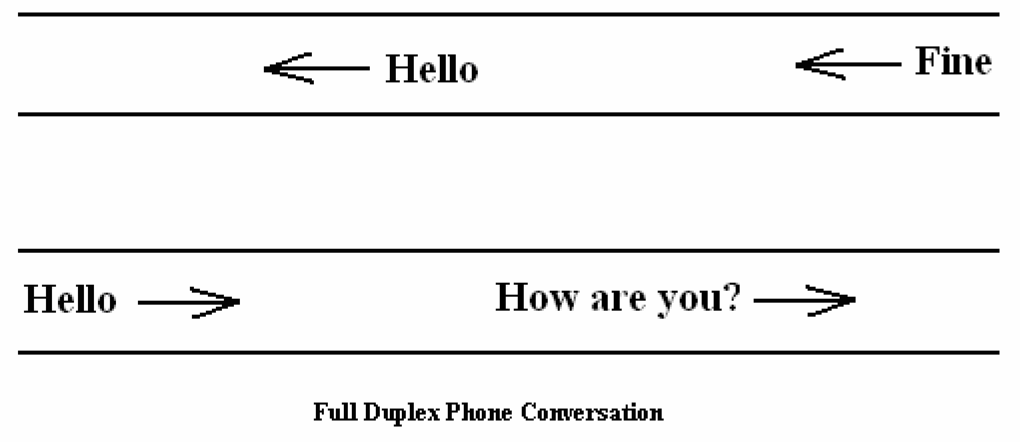


**Figure 5.2. Full Duplex Phone Conversation**

The conversation demonstrated in Figure 5.2 could occur over a T-1 link in each direction, which would mean that the conversation in interspersed with 23 other channels available for other users. The conversation illustrates two additional characteristics that are necessary for a full duplex communication:

1.) A delay associated with the response to the original transmission
2.) Synchronization between **User 1**, the original transmitter, and **User 2**, the responder. The synchronization is to ensure that the response received from **User 2** is not only timely but that the response is applied to the correct outgoing message from **User 1**.

The elements of a full duplex SD communication system are described in the next section.

## 5.1 FULL DUPLEX SD COMMUNICATION

The **User *i*** in half duplex mode will have the transmission characteristics represented by the octuple

$$[\,\mathbf{U_i} \rightarrow\,] = (\boldsymbol{P\ or\ non\text{-}P}, \boldsymbol{c}, \boldsymbol{\rho}, \boldsymbol{\alpha}, \boldsymbol{\delta}, \boldsymbol{j}, \boldsymbol{B}, \boldsymbol{hh.mm.ss.hs.ts})$$

The symbol → is used to indicate transmission in one direction. Similarly $[\,\mathbf{U_i} \leftarrow]$ in the other direction would have a comparable though not necessarily equal set of characteristics, dependent on whether **User *i*** is an SD user or a non-SD user. The communication in the other direction (controller to sampler, destination to source, etc.) is designated the response.

For an SD real time distributed control system, it is anticipated that the response,

1.) Would typically have the same period as the originating transmission. For each sample there is an anticipated response.
2.) Would be continuous or finite based on the originating transmission.
3.) Would have a transmission frequency similar to the originating transmission, only delayed by a known $\boldsymbol{\delta}$ associated with processing and response time.
4.) Would not necessarily have an equal amount of data per transmission as the originating transmission.
5.) Would typically have the same requirements for delay.
6.) Would typically have the same requirements for jitter.
7.) Would typically have the same burst requirements.
8.) May not necessarily have the same date stamp requirements.

The list above indicates that for control systems, there could and probably would be differences in the originating and response transmissions and that these depend on the individual systems, indicating a need to have a separate $\mathbf{[\ U_i \leftarrow]}$ in the response direction. As indicated previously, the $\mathbf{[\ U_i \leftarrow]}$ would be delayed and the delay would need to be specified as part of the full duplex system.

Similarly, the non-SD user would not necessarily have the same requirements in the original transmission as it would have in the response. An example of this would be a web based request that may have a small request for data in the original transmission and a large amount of data in the response.

**User *i*** in half duplex mode on the communication link ***E*** will be characterized by

$$f(E_i) = \text{┼}\ \sin(\omega_i t + \varphi_i) \qquad \text{for} \quad 0 \leq \omega_i t < 2\pi$$

$$0 \leq \varphi_i < \pi$$

The same characterization would be use for both directions of transmissions in the full duplex transmissions. Once the delay between sample and response is determined, the synchronization between channels of originating transmission and response transmission would be possible.

The same admission methodology used to determine whether a user could admitted in the half duplex mode would need to be done to both directions in the full duplex mode, given the probability that the transmissions in one direction would be different than the transmission of data in the other direction, and the user requirements in one direction would be different than the requirements in the other direction.

Thus, the methodology developed in this research can be applied to both directions for full duplex communication with the same guarantees for quality of service.

# 6.0 COMPARISON SUMMARIES

The communication link ***E*** is a composite of some the properties of the T-1 channel and ATM. The T channel and ATM were discussed in Section 1.3. This section compares those technologies to the communication link ***E***.

## 6.1 THE T-1 CHANNEL

The T-1 is a channelized communication link that provides the user a guaranteed path for the transmission of a fixed amount of data. The channels are fixed in size on the T-1, as is the frame size. Each channel is dedicated to one user, and the user's information cannot be moved from the ***ith*** channel to any another channel. Users have access to one channel per frame. Admission by the link is on a first-come-first-serve basis.

The communication link ***E***, in comparison to the T-1, is also a channelized communication link, the purpose of which is to provide a guaranteed communication path for more than one type of user. The channel sizes of the link ***E*** can be varied based on the needs of the users relative to the amount of data that the users will be transmitting. As the link ***E*** is designed for use by Synchronous Dependent users, the assumption without loss to generality is that the data are a fixed size on a per user basis. Resizing the size of the channel on a per user basis is an option to decrease the amount of padding that may be need to fill a frame that does not have enough data to fill the channel.

The size of the frame on the communication link ***E*** is determined by the transmission frequency of the first user (the fundamental user) to be granted access to the link. The purpose of the frame, similar to the T, is to indicate the beginning of the next transmission by the fundamental and the beginning of the next set of transmissions by the other users using the link. The frame on the link ***E*** is more a logical divider as opposed to a physical divider as it is on the T channel. The fundamental user and the frame delineation also serve as a basis for the use of sine waves and phase shifts as part of the link characterizations and the method of analyzing user admission.

In contrast to the T channel, the link ***E*** also supports the shifting of data from on channel to another in order to accommodate other uses on the link. The shifting of channels indicates that the communication link ***E*** will support users with allowances for delay and jitter. The link E also supports SD and non-SD user types, assigning specific channels to the user when the connection is set up.

The users of the communication link ***E*** also can use more than one channel to allow the transmission of data that is larger than the channel size. This enables the link ***E*** to support users with different sizes of synchronous data transfer needs. The communication link ***E*** will support user transfer rates that are faster than the frame rate, in contrast to the standard T-1, which permits one instance of a user per frame.

Admission to the communication link requires the submission of user parameters to determine amongst users which are applying which one provide the greatest return, which users are most compatible with users already accessing the link, and whether the link has sufficient resources to meet the users needs.

## 6.2 ASYNCHRONOUS TRANSFER MODE

Asynchronous Transfer Mode (ATM) uses cells as the data transfer unit, as compared to the channel in link ***E***. The ATM cells are of a fixed size as compared to resizable channels of the link ***E***. ATM does not have frames, as does link ***E***.

ATM provides prioritization of data to provide the guarantee of the delivery of data for certain classes of users; other users get best effort delivery. ATM does not assign a cell to a user, in contrast to the link ***E***. ATM does support the use of contiguous cells by the same user, if the data being transmitted by the user has the highest priority. At what point a cell containing a user's information is transmitted is determined by a scheduler at the entry to the link.

ATM will provide guarantees when the user is admitted for the amounts of requested bandwidth and limitations on delay and jitter. Admission is based on the ATM links ability to meet the requested resources requested by the user. If a user transmits at a higher frequency than what was requested at connection setup, ATM will drop the information so that it can be resent.

Asynchronous Transfer Mode can be viewed as a restricted version of the communication link ***E***. The cells of ATM are a fixed size (link ***E*** can vary), but the cell generator continually generates a stream of cells in much the same way as a continuous stream of channels would be generated. The cell generation is synchronous.

The transmission frequency of the ATM cell is the overall bit rate of the link divided by the size of the ATM cell (53 bytes), such that the $\boldsymbol{\omega}$ for ATM cell rate is fixed, but will vary for the link ***E***. ATM is designed to handle periodic (SD) data transmissions and if the occurrence of a **User *X*** were marked as the beginning of the frame identifying ***X*** as the fundamental user then that would be comparable to the link ***E***.

The primary difference is that the channels in the link ***E*** are designated for a user when the user is admitted to the link; ATM uses the scheduler at the time of transmission to assign data to a particular cell.

# 7.0 CLASSIC EXAMPLE PROBLEM

One of the original motivations for this dissertation was the potential use of an SD network in an ambulatory care facility for the purpose of providing remote monitoring of patients. Ambulatory care was envisioned as either sending the patient home and monitoring the patient remotely or else allowing the patient to move around the facility, connected to the numerous wires associated with medical monitoring devices but transmitting the data over a wireless network utilizing the SD methodology. The patient may be connected to a temperature monitor, heart monitor, or a brain monitor. The information provided by these monitors would be critical to the patient's care. There were several reasons to pursue this area of research.

One of the reasons was that it has been shown that lengthy hospital stays have an adverse effect on a patient's health[50]. In addition, medical costs are continuing to rise and constitute a large percentage of every dollar spent out of personal income and lengthy hospital stays are part of the costs. Medical costs increased 7% in 2003 and the same was estimated for 2004[51] and medical expenses accounted for half of the filings for personal bankruptcy in 2001[52].

Decentralized medicine is being used to provide real time imaging support of patients from remote locations[53]. A T-1 is used to support the transmission of the data in this case. Collaborative medicine is in use to provide access over Wide Area Networks (WAN) for use in transplant pathology[54]. Telemedicine, where a physician at a remote location evaluates a patient condition, has been practice since the 1990s[55].

To support the transmission of the monitoring information, a methodology was needed that would provide a guaranteed delivery of the data due to the critical nature of the data. The transmission methodology would also need to support various transmission rates, as the temperature monitor would not have to be monitored as frequently as the heart rate or other parameters associated with the heart. The transmission methodology would also have to support varying amounts of data transmitted by each monitor, as temperature would require less data than the heart monitor.

Shown in Table 7.1 are several types of devices used for monitoring patients.

**Table 7.1. Patient Monitoring Equipment with Frequency of Transmission and Amount of Data Transmitted**

| **Type** | **Description** | **Freq Range Hz** | **Voltage µV** | **Number of Leads (Inputs)** | **Sampling Rate Hz** | **Total BW Needed (Bytes)** |
|---|---|---|---|---|---|---|
| **EEG**<br>**(electroencephalogram)** | Brain Activity | .5 to 40[56] | 10 to 100[57] | 20[58] | 100 | 2000 |
| **EKG**<br>**(electrocardiogram)** | Heart Monitor | 250[59] | 1000 to 2000[60] | 12[61] | 1000 | 12000 |
| **EMG**<br>**(electromyogram)** | Muscle | 15 to 150[62] | 3 to 2000[63] | 2[64] | 400 | 800 |
| **Respiration Rate** | Breathing Rate | .1-10 | NA | 1 | Variable | 20[65] |
| **Body Temp** | Body Temp | Variable | NA | 1 | 40[66] | 40 |
| **Heart Rate** | Heart Rate | 40 to 120 | NA | 1 | .16 | .16[67, 68] |
| **Blood Pressure** | BP | 0-50 | NA | 1 | 100[69] | 100 |

The table shows that the range of frequency transmission varies from .1 to 1000 Hz and the amount of data transmitted varies from one byte to 12 kilobytes per transmission. If the monitoring device is intelligent, it may not be necessary to send every sample but only the average of several samples.

In support of the communication needs shown above, and SD link may even be able to operate in a half duplex mode, as the majority of the communication will be from the monitoring sensor to the recording device at the remote location (hospital, doctor's office, ambulatory care center). If there is a real time clock associated with the sensor attached to the patient, it would not even be necessary for the recording device to poll for the monitoring device to transmit the data.

If the data were being transmitted over a wireless link, an analysis would have to be performed as to how many patients could be supported. The admission control methodology would be required to not only admit users to the link but serve as part of the system that monitors the transmission units as the patients roam between access points. The implementation of such a system over wireless could be considered for future research.

Once the sampling rates are established for one patient, additional patients on the same monitoring regime are simply entered as phase shifted signals (in the sense of the location of the channel in which they are included) with respect to to first user in the context of this research.

The ability to remotely control devices on and around the patient likewise are feasible and can easily be made a part of the link back to the patient.

One of the current applications of high speed communications is the transmission of medical images. When transmitted as an image, the entire image is captured and framed for proper reconstruction on the screen at the destination. The only question of dynamics in this case is the delay in which the single image is available for projection. The same is not true for the real time monitoring of vital signs and other patient monitoring devices which must be delayed to be captured as an image which is transmitted to the destination. The research reported in this dissertation provides the basis for communicating these signs and other measurements in real time to give the most accurate status to the monitoring physician at a remote location.

The ability to operate the link in the direction of the patient will thus open up a full scale real time control system for remote medical applications.

# 8.0 SUMMARY CONCLUSIONS, CONTRIBUTIONS, LIMITATIONS, AND FUTURE RESEARCH

## 8.1 SUMMARY AND CONCLUSIONS

The purpose of this research is to provide a method to characterize and model a highly Synchronous Dependent (SD) communication link capable of guaranteeing the delivery of data transmissions for applications that are sensitive to the delays associated with network-based communication systems. A highly Synchronous Dependent communication link is one that would service users that collectively are largely periodic with deadlines associated with the transmission of their data. In addition to the communication link, the users of the link would also be characterized and modeled. Admission to the link would be determined be a method of analysis that would determine the suitability of the user requesting access relative to those users already admitted to the link. The use of the communication link is to be maximized so as to make it commercially viable. To provide commercial viability, the link would also have to service users with less stringent requirements.

The communication link is a channelized link similar in form to a T-1 with channels continuously generated. The modeling of the link is conceptually in the form of a sine wave, where each channel was generated at the zero-crossing of the sine wave. Initially the link would be modeled as a series of sine waves, but it has been shown that there were advantages to modeling the link as a sine wave and that each channel would be a phase shift relative to an originating (fundamental) channel.

The users of the communication link were also modeled using a sine wave with phase shift. The first user to be granted access to the communication link was termed the fundamental user and the transmission frequency of the fundamental was used to form frames made from the channel containing the fundamental user transmission and all channels up to the next transmission of the fundamental user. The significance of the frame was to show the repeatability of the highly Synchronous Dependent and to serve as a delimiter for the phase shifts marking the additional users. It was shown that each subsequent user of the link was limited by the size of the frame (and the transmission of the fundamental user). Users that were a multiple of the fundamental would easily integrate into the frame as long as there were channels available, while non-multiples introduced the delay and/or jitter of other users already accessing the link.

The users are characterized by eight parameters that reflect whether the user is SD or non-SD, continuous or finite, the frequency of transmission, the amount of data per transmission, whether there are requirements for delay, whether there are requirements for jitter, is there burstable data, and is there a time stamp associated with the data. Users were also characterized as to whether they were multiples of the fundamental and the effect this would have on the other users using the link.

The effect of admission of a particular user is analyzed by a method developed on link and user characteristics that are associated with the communication link to determine which user should be the fundamental user, the reward associated with admitting users after the fundamental, and which users have the potential for successful placement in the link relative to the users already granted access to the link.

The choosing of the fundamental user could potentially be based on *a priori* knowledge of the characteristics of the users of the link, and is such knowledge does not exist, some other parameter determined by the link operator. An example of a rewards based system to determine based on the characteristics was also provided.

The admission of users after the fundamental was based on the probability of a type of user requesting access to the link. From the state diagram it is possible to determine the transition from the current state to the next state. The probability of the next state is related to the current state but is independent of the previous state, making this a Markov process.

A rewards system can then be associated with the user types and applied to the state transitions to demonstrate the effect of admitting one type of user as opposed to another type. From the probability and the rewards associated with the users and state transitions, it is possible to compute a gain, from which can be determined the effect of admitting one type of user compared to another.

The SD communication link is then compared to a T-1 and ATM services, comparing and contrasting the three types of services. The appropriateness of the use of the SD network in an ambulatory care facility was then discussed.

## 8.2 CONTRIBUTIONS

The contributions of this dissertation are the characterizations of the potential users of the proposed SD link in a manner that allows the mathematical description of the users and the associated state transitions, as well as the rewards for making these transitions. The characterization of the users also provides information relative to the interactions of the users based on their user parameters as described by the octuple. The characterization of the users also permits a description of the link as an aggregation of the different user types. This research also provides the implementer a methodology to evaluate alternatives when presented with multiple types of users.

The model has been mathematically constructed, and as such, the structure is correct in the current form based on the previous established Markov process analysis. Examples in this dissertation are going to be arbitrary until a specific system is chosen as a candidate for an application. The recommended proposed application for future work is sensor communications from a nuclear reactor containment system.

## 8.3 LIMITATIONS

The SD communication link is designed to have the periodic SD user with the longest time between transmissions as the fundamental user. This user's transmissions will define the frame length on the link. If an SD user is admitted with an $\omega_i$ (transmission frequency) << $\Phi/2\pi$ (channels per unit time/$2\pi$), the frame size on the link will be extremely large. An extremely large frame size will have a large number of phase shifts relative to the fundamental. The larger the number of available phase shifts and locations to place the user data, the longer the computational time may be required to place the data in the channel and the more difficult it is to shift the data due to delay and jitter.

When the frame contains fewer channels than $\Phi$ there are fewer occurrences of each SD and non-SD user in the frame. As the frame size increases the more difficult it may be to monitor the location of the transmitted data.

The scenario where $\omega_i \ll \Phi/2\pi$ can be potentially resolved by setting a maximum frame size and treating the SD user with a large number of channels between transmissions as a non-SD user.

## 8.4 FUTURE RESEARCH

One of the primary areas for future research involves the formulated modeling technique of this research to be able to analyze other communication links in term of frequency content based on the corresponding sine waves that would result from their attendant scheduling algorithms and policies for controlling admission. An additional area of future research is to identify an SD network such as the dynamic medical monitoring and compare the user types in this dissertation with the actual network. From this network it would be possible to better determine the actual probabilities of the state transitions to determine the rewards associated with admitting a a certain user type. Additionally, identifying a particular type of network (802.11, Ethernet, etc) to serve as a prototype for the implementation of the SD methodology and potentially determine the effectiveness of the SD network in a situation similar to the ambulatory care facility.

Another area of research is the use of the SD communications methodology in support of a serial communication link from inside a nuclear containment vessel. The containment wall is comprised of six feet of concrete. Drilling a whole through the containment wall is extremely expensive. Therefore, the Physical Layer data transmission will occur using a modulated signal over the existing power lines. Currently, the anticipated available bandwidth is sixty bits per second. This may be increased using dibits or quadbits by mixing amplitude modulation with frequency modulation. The use of the SD communication methodology will allow data transmissions of varying frequency and data length to multiplexed onto the power lines to provide sensor readouts from inside the containment area.

In conclusion, the description and mathematical analysis of the SD network provides a viable option in network design for use where time-sensitive data will be transmitted in an environment that contains multiple types of highly synchronous SD users.

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