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Bandwidth Management in Indoor Broadband Wireless Networks (IBWN)

by:

Naser Movahhedinia, B. Sc., M. Sc.

A thesis submitted to

the Faculty of Graduate Studies and Research

in partial fulfillment of

the requirements for the degree of

Doctor of Philosophy

Ottawa-Carleton Institute for Electrical Engineering

Faculty of Engineering

Department of Systems and Computer Engineering

Carleton University

November 1995

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Chair, Department of Systems and Computer Engineering
Professor Samy A. Mahmoud

Thesis Co-Supervisor
Professor Roshdy H. M. Hafez

Thesis Co-Supervisor
Dr. Georgios Stamatelos

External Examiner
Professor Ahmed K. Elhakeem
Department of Electrical and Computer Engineering, Concordia University

Carleton University
November, 1995

ABSTRACT

One of the recent issues in wireless communications is to support multimedia applications in a broadband ATM platform. In such a system remote terminals may be capable of producing broadband real-time traffic such as variable bit-rat video or bursty instantaneous file transfers. Comparing to wired medium, the bandwidth in wireless medium is more expensive, so an efficient bandwidth management procedure is required for the wireless broadband ATM networks. To obtain the required performance, the effects of radio channel behavior as well as the traffic heterogeneity have to be considered in the bandwidth control procedure. As such, the simple conventional multiple access protocols may not offer adequate flexibility and performance. The scope of this thesis is to present a proper bandwidth assignment regulation, meditating on the interplays of the radio channel characteristics, the traffic statistical parameters and the traffic Quality Of Service (QOS) requirements. Initiating from the simple non-limited polling scheme, the performance of the multiple access protocol is improved, with an analytical backup, to a graceful method which utilizes all the mentioned parameters. The investigation has come up with two multiple access methods in which the base station visits the remote terminals in a non-uniform cyclic fashion. The basic properties of these two methods which are called "*non-uniform polling*" and "*non-uniform slot reservation*" are as the followings:

- unequal visiting cycle for different types of traffic, and limited service provided to each user during a visit,
- determining the visiting cycle and service limit in each cycle based on the radio channel characteristics, the user traffic parameters and the user QOS requirements,

The bandwidth management is further completed by presenting a virtual bandwidth for a given type of traffic, based on which the admission control procedure is performed.

The performance of the non-uniform polling and the non-uniform slot reservation is evaluated and compared with some other techniques by simulations.

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Table of Abbreviations

ACI	adjacent channel interference
AR	auto-regressive process
ARMA	auto-regressive moving average process
ARQ	automatic repeat request
ATM	asynchronous transfer mode
BCT	the basic cycle time in non-uniform slot reservation method
BER	bit error rate
BPC	the basic polling cycle in non-uniform polling
cdf	the cumulative distribution function
CBR	constant bit-rate traffic
CCI	co-channel interference
CDMA	code division multiple access
CFR	the average channel failure rate
DS	delay spread
FDMA	frequency domain multiple access
FGL	fully gated limited (polling)
FEC	forward error correcting technique
HDTV	high definition TV
IBP	interrupted Bernoulli process
IBWN	indoor broadband wireless networks

Table of Abbreviations

Mbps	mega bit per second
MMBP	Markov modulated Bernoulli process
MTD	maximum tolerable (transfer) delay
NRTT	non-real-time traffic
NUSR	non-uniform slot reservation
PCS	personal communications systems
QOS	quality of service
RTT	real-time traffic
SNR	signal to noise ratio
TDD	time division duplex method
TDMA	time division multiple access
TES	transform-expand-sample method
VBR	variable bit-rate traffic

Table of Notations

AR	the activity ratio of the mini-sources used in modeling a source
$\{a_k(t)\}$	the random time-varying amplitude of multipath components
B_{max}	the buffer limit
$\bar{C}$	the mean cycle time
C_i	the number of slots in the i^{th} polling cycle
C_j	polling cycle for active user j
C_L	the cycle time limit
CFR_j	the average channel failure rate for remote j
$\bar{D}_j$	the mean waiting time for the jobs present in the queue at the polling instant
δ	the delta function
$\bar{\epsilon}$	the probability of producing a cell in a time slot for a mini-source
$f_r(r)$	the probability density function (pdf) of the signal amplitude at the receiver
G_j	the service time allocated to user j in the <i>BPC</i>
γ	the cell-rate generated during the ON state of a mini-source
γ_j	the cell-rate generated during the ON state of a mini-source of source j
$\Gamma(.)$	the Gamma function
η_{Th}	the fade margin defined as the ratio of the average signal amplitude to the fade level

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I	the power of interference
I_o	the zero-order modified Bessel function
k_j	the service limit for j^{th} user
k_j	the maximum number of the slots provided to user j in each visit
K	the total service time in a cycle
m	the number of users to be visited in the <i>BPC</i>
M	the number of mini-sources used for modeling a source
M_j	the number of mini-sources used for modeling source j
MTD_j	maximum tolerable (transfer) delay for user j
μ_r	the mean of logarithm of large scale variations of signal amplitude in multipath environment
$\bar{\mu}_j$	the mean cell arrival of the j^{th} source during a time slot
$\mu_j(n)$	the number of cell arrivals for remote j at time slot n
$\mu_{i-1,j}(n)$	the cell arrival rate for remote j at time slot n , during the polling cycle $i - 1$
N	the number of communicating remotes
N_T	the power of thermal noise
$N(\tau)$	the number of multipath components
p	the probability of remaining in ON state in the next slot for a mini-source
p_j	the probability of remaining in ON state in the next slot for a mini-source of source j
$\bar{P}$	local mean power
P_{fade}	the probability of being in a fade
P_r	the instantaneous received power

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P_E	the probability of emitting a cell in a time slot by one of the mini sources in a symmetric cyclic system
P_{loss}	the target cell loss probability
P_t	the total received power
PR	the peak-rate of a source
π_{ON}	the probability that a mini source is in ON state
q	the probability of remaining in OFF state in the next slot for a mini-source
q_j	the probability of remaining in OFF state in the next slot for a mini-source of source j
$QL_{i,j}$	the queue length at the polling instant for j^{th} user in cycle i
$R_j(n)$	the autocorrelation of cell arrivals for source j at time slot n
ρ	the channel utilization defined as the ratio between the total offered load and the available capacity (the probability of having a new cell in a time slot from any of the connected remotes)
ρ_G	the utilization under which the cell loss and delay requirements of the connected sources are guaranteed
ρ_{max}	the maximum utilization which is supported by a network
s	the overhead for each user served in a given cycle in symmetric system
$\bar{S}$	the total mean overhead
S_i	the overall polling overhead in the i^{th} polling cycle
σ_{ζ}^2	the variance of the channel failures
σ_{μ}^2	the variance of the cell generation rate for a user in symmetric system
σ_{ϵ}^2	the variance of cell arrivals in a time slot for a mini-source

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σ_r^2	the variance of the logarithm of large scale variations of signal amplitude in multipath environment
$\sigma_{w_j}^2$	the variance of the number of slots allocated to user j
$\sigma_{V_{HL}}^2$	the variance of the queue length at the arrival of the server to each queue in a symmetric cyclic system under heavy load situation
t	the observation time of multipath impulses
T_d	the fade threshold
T_j	the service time requested by user j in a <i>BPC</i>
T_{OFF}	the averages of OFF periods of a mini-source
T_{ON}	the averages of ON periods of a mini-source
τ	the application time of multipath impulses
$\bar{\tau}_{NF}$	the mean non-fading duration
$\bar{\tau}_F$	the mean fade duration
$\{\tau_k(t)\}$	the random time-varying arrival-time of multipath components
$\{\theta_k(t)\}$	the random time-varying phase sequences of multipath components
$U_{i,j}$	the unfinished work at the end of service time
$U_{i-1,j}$	the unfinished work in cycle $i-1$
$V_{i,j}$	the number of cells which the base station finds in j^{th} remote queue at the polling instant in cycle i
$\bar{V}_{HL}$	the mean queue length at the arrival of the server to each queue in a symmetric cyclic system under heavy load situation
VBW_j	the normalized virtual bandwidth for the user j
$\bar{W}$	the mean service provided to each user in a symmetric cyclic system
$\bar{W}_j$	the mean number of allocated slots to user j

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$W_{i,j}$	the number of slots allocated to (served cells from) user j during cycle C_i
ω_m	the Doppler frequency shift
$\bar{\xi}_p$	the percentage of erroneous cells due to channel failure
$\bar{\xi}_j$	the mean number of failed slots for user j during a cycle
$\xi_{i-1,j}$	the number of the slots which are not available to remote j due to channel failure during the $(i-1)^{th}$ cycle

Chapter 1

Introduction

1.1 Indoor Broadband Wireless Networks (IBWN)

Mobile communications has been successful in inducing considerable satisfaction in terms of flexibility and mobility of the users. This satisfaction has caused a growing interest in wireless in-building communication systems. The indoor wireless networks bring about attractive advantages such as easy deployment, and low cost re-configuration of the system. This is in contrast to wired networks in which establishment and redeployment of the system is accompanied with high cost of labor, rewiring and materials. Another benefit is the mobility of users and equipments.

Sofar, most of the work in this area has been focused on voice and data applications. But the rapid development of personal communications systems (PCS) is widening the scope of applications to more broadband and complicated traffic, such as variable bit-rate (VBR) video or bursty file transfers. Future networks may have to support 20 Mbps (mega bit per second) VBR video [39], with a burstiness (peak to mean bit-rate ratio) of up to 5.

The main issues in indoor broadband wireless networks (IBWN) are:

- 1- The radio propagation environment imposes a number of difficulties. The reflections by walls and other objects in a room, the shadowing (obscuring the line of sight between transmitter and receiver), and the propagation loss are the common causes of those difficulties. Another problem is the interference caused by adjacent radio communications in spatial, time, or frequency domains. The basic issue here is how to overcome these effects and provide a low error level at the output of the receiver.

2- The second issue is how to manage the bandwidth among the active users. This is again a difficult task. The user density within a building is much higher than outdoor, and their traffic requirements could be very diverse. The bit rate of the source may vary from the low of 16 kbps to the high of 20 Mbps. Obviously employing an efficient bandwidth assignment procedure is very crucial.

1.2 The Multiple Access Protocol

There are many multiple access techniques proposed for the wireless communications which can be categorized in three main alternatives: frequency domain multiple access (FDMA), code division multiple access (CDMA), and time division multiple access (TDMA). FDMA, although presently is used in narrow-band wireless systems [12], is recognized to be unsuitable for IBWN. To accommodate services with different bit rates, and to perform statistical multiplexing and dynamic bandwidth allocation, FDMA requires fast change in channel bandwidth which is very difficult to implement. Besides, it is very costly to generate carriers, and change filters pass-bands at millimeter waves.

CDMA and TDMA offer better alternatives. The issue of selecting one over another is yet to be resolved [12]. CDMA systems are claimed to be capable of accommodating more sources than TDMA [23]. CDMA doesn't require explicit bandwidth reservation at the burst level, so statistical multiplexing implementation is simpler. Overload situation in CDMA leads to an increase in degradation of the service quality which is shared by all terminals, while in such a situation TDMA tends to be degrading or dropping some of the sources, especially the bursty ones [65]. However, supporting the chip-rate for high bit-rate services may be difficult to implement, so CDMA has the disadvantage of relatively low peak transmission bit-rate compared to TDMA, which is a difficult problem in multimedia communications. Besides, to obtain a fair bandwidth sharing among the far and near remotes, CDMA requires "power control" which is a complex and costly procedure [19]. A non-power controlled version of CDMA/ALOHA, with low processing gain, was found to be less efficient than a TDMA-based protocol for broadband mm-wave access [114], and power control has not improved the efficiency sufficiently to justify its higher cost and complexity [18]. In this thesis, TDMA is chosen as the proper multiple access protocol for the system under research.

1.3 The System Specifications

A typical diagram of the system is shown in figure 1.1. A single floor is divided into radio cells. Each cell is served by a single station. The stations are connected to a broadband ATM wired network by an ATM switch. There is a limited number of remotes in each cell which are capable of generating various types of traffic (in general video, voice, and data). We assume that the remote terminals communicate only with their home base station on a millimeter wave radio link. We focus on the multiple access and bandwidth allocation procedures only in a single cell. However the interference from adjacent area cells can be considered.

To acquire necessary flexibility in supporting various types of traffic, and simplify the integration of IBWN with the wired backbone network in a common platform, we consider asynchronous transfer mode (ATM) standards as the basis for transmission protocols. Congenially ATM cell is considered as the basic unit of the transferred data.

The polling scheme seems to be a suitable method to allocate the time slots to the connected remotes, in a cyclic fashion within a TDMA frame. In the method which we consider the traffic is managed by the base station as the central controller. By polling the users, the base station is able to carry out the statistical multiplexing utilizing the "up to date" information about users buffer contents. It provides the base station a full control over the bandwidth management procedure, and allows the priority to be given to delay sensitive connections gracefully.

1.4 Outline of The Thesis

The main focus of this research is on the bandwidth management for the IBWN in a TDMA platform. Since the characteristics of channel behavior have a considerable impact on the system performance, some aspects of the radio signaling will be discussed in the second chapter. In chapter 3, brief backgrounds on multimedia traffic modeling and polling based multiple access protocols are presented. Then, we show analytically and by simulation that for a heavy load of bursty, delay sensitive traffic, non-limited service assignment offers poor performance, leading to high loss and high average delay. In

Figure 1.1 Typical diagram of the system

chapter four, the limited service assignment in a gated-limited polling fashion is examined and we show that for a certain mixture of traffic there is an optimum limit for the cycle time. To lessen the drawback of the polling overhead, we introduce the idea of nonuniform polling, and illustrate through the simulations that non-uniform polling improves the performance of the system. Chapter five is appropriated to analyzing the symmetric fully gated limited (FGL) polling system which results in an upper bound on the utilization which guarantees the user QOS requirements, considering the effects of the source burstiness and the average channel failure rate. In chapter six the bound on the channel utilization, obtained in chapter 5, is put to use to determine the suitable polling period and the sufficient number of allocated slots to each user. Then the performance of the non-uniform polling scheme is evaluated by simulations and compared to some other polling techniques. Furthermore, an equation is derived for the virtual bandwidth which is required to obtain a guaranteed connection quality for a given type of traffic. This virtual bandwidth will be used for admission control procedure. Next, the idea of non-uniform service assignment is extended to a reservation based scheme called the Non-Uniform Slot Reservation (NUSR). The procedures of admission control and bandwidth allocation for the NUSR scheme are explained in details and the performance of the non-uniform polling and the NUSR are compared. In the last chapter the thesis is concluded and the contributions are summarized and some suggestions for the future research are presented.

Chapter 2

Indoor Wireless Medium

2.1 Introduction

The indoor radio channel exhibits various kinds of distortions, which may be:

- 1- Flat and frequency selective fading caused by delayed copies of the transmitted signal overlaying at the receiver. These copies are generated by reflections and deflections of the transmitted signal by walls and moving and fixed objects and people (multipath), and shadowing originated by propagation losses and covering the line of sight between base and remotes.
- 2- Interference with communications in other cells, originating either from the same frequency band (co-channel interference) or neighboring frequency bands (adjacent-channel interference).

In the next sections these factors will be explained briefly.

2.2 The Channel Characterization

The radio channel impulse response, in its complex form, can be modeled for each point in the three dimensional space, by the following linear time-varying filter:

$$h(t, \tau) = \sum_{k=0}^{N(\tau)-1} a_k(t) \delta(\tau - \tau_k(t)) e^{j\theta_k(t)} \quad (2.1)$$

where t and τ are the observation time and application time of the impulses. $N(\tau)$ is the number of multipath components. $\{a_k(t)\}$, $\{\tau_k(t)\}$, $\{\theta_k(t)\}$ are the random time-

varying amplitude, arrival-time, and phase sequences, respectively, and δ is the delta function.

Assuming that the channel impulse response components are slowly varying in time, the stationary (time-invariant) model of the channel can be written as:

$$h(\tau) = \sum_{k=0}^{N(\tau)-1} a_k \delta(\tau - \tau_k) e^{j\theta_k} \quad (2.2)$$

The sudden appearance of these components is analogous to a Poisson process. So the inter-arrival time has an exponential distribution. To take into account the clustering property of paths made by a group of scatterers, the double Poisson model has been proposed, and the empirical data collected in an office building has been shown to fit well to that model [85,86]. In this model the cluster intervals and the arrival times of the components within a cluster are modeled by exponential distributions.

The small-scale fluctuations of the amplitude of the impulse response components, in absence of one strong component, are commonly modeled by the Rayleigh distribution. For a cluster of Rayleigh scatterers, the probability density function (pdf) of the signal amplitude at the receiver is given by:

$$f_r(r) = \begin{cases} \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} & r \geq 0 \\ 0 & r < 0 \end{cases} \quad (2.3)$$

where $\sigma^2 = \frac{1}{2} E\{r^2\}$ is the local mean power.

In the case of a strong multipath component, whether it is originated from the line of sight path or a path that goes through much less attenuation, the fluctuations has the following Rician distribution:

$$f_r(r) = \begin{cases} \frac{r}{\sigma^2} e^{-\frac{r^2 + v^2}{2\sigma^2}} I_0\left(\frac{rv}{\sigma^2}\right) & r \geq 0 \\ 0 & r < 0 \end{cases} \quad (2.4)$$

where I_0 is the zero-order modified Bessel function, v is the magnitude of the strong component and σ^2 is proportional to the power of the Rayleigh component.

For the signal accumulated from several Rayleigh fadings with arbitrary local-mean power levels, the Nakagami distribution model is proposed which is in the form of:

$$f_r(x) = \frac{x^{m-1} \cdot e^{-\frac{x}{2\sigma^2}}}{(m-1)! \cdot (2\sigma^2)^m} \quad x \geq 0 \quad (2.5)$$

where $x = r^2$. For $m = 1$ the Nakagami distribution reduces to Rayleigh distribution.

The large-scale variations of the signal amplitude in multipath environment is approximated by the lognormal distribution, where its pdf is obtained by:

$$f_r(r) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma_r \cdot r} e^{-\frac{(\ln(r) - \mu_r)^2}{2\sigma_r^2}} & r \geq 0 \\ 0 & r < 0 \end{cases} \quad (2.6)$$

The logarithm of the variable r in (2.6), $\Gamma = \log_{10}(r)$ has Gaussian distribution with mean μ_r , and variance σ_r^2 .

The r.m.s. (root mean square) delay spread (DS) defined as the square root of the second central moment of the power delay profile, is a good measure of multipath spread. Excessive DS causes severe inter-symbol-interference, and in this case a complicated anti-multipath signalling would be required [28]. The DS is affected by some parameters of the system. The larger the size of the room, the larger the DS [100]. Antenna directivity may

reduce the DS, and a higher transmission power results in a higher DS profile [77,94]. The median value of the r.m.s. DS observed with a centrally located transmitter varies from 25 ns in a medium-size office building to about 125 ns in a large office building [85,86].

Due to people's and objects movements, the indoor radio channel is not stationary in time or frequency domains, but since neither terminals nor people move quickly, the doppler shift is negligible. Path loss is very severe within a confined room, being between 65 to 85 dB [91]. Although for close points in space, the impulse response profiles are correlated, but distanced terminals may experience independent channel parameters [31].

2.3 Improving Signal to Noise Ratio (SNR) at The Receiver

To mitigate the fading effects, A number of techniques have been proposed. Here we only explain in brief, the methods which may be referred to in the next chapters.

2.3.1 Diversity

One well-known method to reduce the fading effects, is the diversity reception technique, which may be applied at the base station, remote terminals, or both. The idea behind diversity is that if two or more independent samples of the signal are taken, they would be faded in un-correlated manner. So the probability of getting unacceptable SNR out of these samples is p_f^m where p_f is the probability of having one of the samples less than the acceptable level, and m is the number of samples. Therefore if the m -branch diversity is done perfectly, the fading effect would be reduced exponentially by a factor m .

The diversity may be applied in frequency, polarization, time, or space. The first two methods (frequency and polarization diversity) are found to be either difficult, or inefficient [77,42]. The last two methods, are commonly used, and are briefly explained in the following sections.

Space Diversity:

In space diversity, separate antennas are used to get independent receptions of the signal. The separation is about a half wave-length, which is quite practical for millimeter waves. One attractive way is using directional antennas, each one aiming at a different angle, and

all together covering the whole space of the room. Due to the reflections from walls and objects, the radio emission from each of the antennas reaches all points in the three dimensional space (figure 2.1). Because of the different path from each antenna to the receiving point, the receptions are most likely to exhibit independent fading. Utilizing the directional antenna is also beneficial in terms of higher antenna gain (i.e. lower required transmission power to cover a certain distance), and more advantageous due to a smaller delay spread profile.

Another issue in space diversity is how to combine different receptions. In selection diversity, which is the simplest choice, the signal with the highest instantaneous SNR is used. So the output SNR equals that of the best intercepted signals. In practice, the system cannot function on a truly instantaneous basis, but the selection intervals should be shorter than the fading rate [77]. In *ALTAIR*¹, the base and terminals, both have the hexagon sectored antennas shown in figure 2.2. Periodically the base sends beacon signals from all its six antennas to the remotes, so that the remotes are able to rank the quality of the reception of each of their antennas from each of the base antennas. The base and the remotes record the ranking in a table, and update the table by averaging the signal quality of the most recent samples with the corresponding values in the table, to provide a somewhat historical perspective of an antenna pair. Each remote terminal can thus select the antenna pair which yields the highest quality signal path, through which to communicate with the base station [8].

Another method is using a phase array antenna at the base station, aiming the main lobe of the antenna toward the communicating remote. The weights of the phase array antenna are adjusted for each remote, by receiving test signal from the remotes periodically [117].

Other common choices of combining diversities are the maximal-ratio combining, and equal-gain combining. In maximal-ratio combining, each signal is weighted in proportion to its own signal voltage to noise-power ratio, then the results are added together to yield the output signal. Equal-gain combining is similar to the maximal-ratio, except that there is no attempt at weighting the signals before addition [77,42].

1. *ALTAIR* is the wireless indoor network for voice and data traffic, designed, and manufactured by Motorola.

Figure 2.1 Receptions of a hexagon sectored antenna at a test point in a room

Figure 2.2 Receptions of the base station transmissions at the remote terminal antenna

Automatic Repeat Request (ARQ):

Although other measurements may be taken to decrease the cell error rate, the ARQ seems to be necessary to obtain the cell loss probability of 10^{-4} which is the least requirement for many of the multimedia services. The transmission path in IBWN is very short, leading to small transmission delay. So despite the out-door communications such as satellite transmissions, in indoor systems the ARQ is recommended even for real-time traffic such as voice and video [65]. To overcome any potential problem due to changes in propagation environment, the selective retransmission is performed and found to be more effective than forward error correcting (FEC) techniques [65].

Other Techniques:

Two other common techniques which may be applied to bring about further decline in error-rate at the receiver, are *channel equalization* and *error correcting coding* [19].

2.4 Channel Model

The received signal envelope experiences very deep fades only occasionally in which the outage rate rises up very rapidly [42]. And also, for a given value of the average SNR, a small increase in outage probability corresponds to a jump in bit error rate (BER) [86]. Thus it seems reasonable to approximate the behavior of the channel by two states: fade/non-fade (or ON/OFF) model, regarding the received signal to noise ratio going down a certain threshold value [86].

Shadowing and fading are slow processes relative to the data rate. If a remote encounters a deep fade in a given multiplexing cycle, it loses the data in that cycle, and may face with the same channel conditions in the following cycle. There must be a mechanism that mitigates these effects (e.g. antenna diversity), otherwise the link will be rendered useless for a long time. Ideally the trend is to design the system such that the channel conditions seen by each remote are independent from cycle to cycle. This, however needs a fast reaction to channel impairments. Therefore, the distribution of ON and OFF intervals are affected by the techniques which are taken to combat the channel failures. In the next sections, we present an overview on the behavior of fade/non-fade durations.

2.4.1 Non-fade Duration Characterization

The multipath measurements and indoor radio channel modeling imply that the fading at millimeter waves can be characterized by slowly varying, frequency selective, Rayleigh fading [86,58]. For a Rayleigh fading, one can simply show that the instantaneous received power, $P_r = \frac{1}{2}r^2$, (where r is the amplitude of the signal at the receiver) has an exponential distribution which is given by:

$$f_{P_r}(P_r) = \frac{1}{\sigma^2} e^{-\frac{P_r}{\sigma^2}} \quad (2.7)$$

Suppose that the non-fade period is the duration in which the signal to noise ratio at the receiver is more than the detectable level. Having the exponential distribution for P_r and assuming the memoryless thresholding, the probability of P_r going below the threshold is independent of the history of the process. Therefore the distribution of the non-fade duration is exponential as well. In [58] the above conclusion is postulated for the general situation when memoryless thresholding is assumed. Therefore, the pdf of the non-fade duration can be expressed as:

$$f_{\tau_{NF}}(\tau_{NF}) = \frac{1}{\bar{\tau}_{NF}} e^{-\frac{\tau_{NF}}{\bar{\tau}_{NF}}} \quad (2.8)$$

where the $\bar{\tau}_{NF}$ is the mean non-fading duration.

In a more general case, in which the multipath interference is a combination of n independent Rayleigh distributed signals with identical local mean power ($\bar{P}$). The Laplace transform of the total power pdf can be written as:

$$\mathbf{L}(f_{P_r}(P_r)) = \left(\frac{1}{1 + s\bar{P}} \right)^n \quad (2.9)$$

So the total received power, P_r , has Erlang pdf given by:

$$f_{P_r}(P_r) = \frac{P_r^{n-1}}{(n-1)! \cdot \bar{P}^n} e^{-\frac{P_r}{\bar{P}}} \quad (2.10)$$

For the case of joint power of n interferers with different local-mean power levels, it is shown also that the total power pdf can be approximated by Erlang distribution [58]. The same equation can be derived for non-fade duration in general situations, leading to Erlang pdf again.

The average non-fade duration for n independent Rayleigh interferers is given by [58]:

$$\bar{\tau}_{vF} = \eta_{Th} \cdot \frac{\sqrt{2\pi}}{\omega_m} \cdot \frac{\sqrt{n}\Gamma(n)}{\Gamma(n + \frac{1}{2})} \quad (2.11)$$

where ω_m is the Doppler frequency shift, $\Gamma(\cdot)$ is the Gamma function, and η_{Th} is the fade margin defined as the ratio of the average signal amplitude to the fade level.

The methods employed to mitigate the fading may affect the statistical behavior of the non-fade duration. Therefore, to obtain more precise model for non-fade durations, one may consider the effects of fade relieving method as well.

2.4.2 Fade Duration Characterization

For a group of n Rayleigh fading, the average fade duration is given by [58]:

$$\bar{\tau}_F = \eta_{Th} \cdot \frac{\sqrt{2\pi}}{\omega_m} \cdot \left[\left(1 + \frac{1}{\eta_{Th}^2 \cdot n} \right)^n - 1 \right] \cdot \frac{\sqrt{n}\Gamma(n)}{\Gamma(n + \frac{1}{2})} \quad (2.12)$$

where the terms are as defined for equation (2.11).

However a deep fade in indoor channel can last for a period ranging from a few milliseconds to several seconds, or even minutes [86]. Obviously such a long period fade brings about unacceptable loss in transmitted cells, and has to be mitigated by suitable reactive measures. As such, the fading duration characteristics depends dramatically on the arrangements actuated to regain the signal from fading. When the signal is so buried in fade that the receiver is not able to reconstruct the transmitted cells, there should be a way to notify the transmitter of the channel condition. The mechanism of notification may be performed by one of the following methods:

1- The control packets are transmitted via the same channel through which the base and the remotes are communicating. If the channel fails, the receiver finds out the problem when it receives erroneous cells, or the time assigned to receive the data from the other party expires. The transmitter finds out the problem when it doesn't receive acknowledgment from the receiver. At the end of the frame the remote should have the opportunity to switch to a good connection (e.g. by using another pair of sectors in sectorized antenna, or changing the weights in phase array antenna). In such a system the multiplexing frame is chosen to be short, so that if a connection experienced deep fading, the number of the lost slots would be small. The "acknowledgment", "time out", and "connection re-establishing" are time consuming, and the method may not be efficient for heterogenous, heavy load traffic.

2- The second approach is to have a separate, very reliable channel for control messages. This channel may use a narrow section of the frequency band [90], or in the same band but with high quality communications obtained by elegant diversity/coding techniques [65]. If the channel is TDD, in the former method, the receiver has to wait for its turn to send the control message. However, in the separate channel method, the receiver informs the transmitter of any channel impairment as soon as detects it. As such, the transmitter makes the proper arrangements to recover the connection. For such a system, one can assume that the fading has approximately a fixed period.

2.4.3 Interference

Since the bandwidth required to support the multimedia traffic is relatively high, the frequency reuse factor could be low. Therefore the same frequency band may be used by "not so distanced" area cells. That may bring about some co-channel interference (CCI). Furthermore, bandwidth spread caused by multipath, may introduce adjacent channel interference (ACI) as well. The characteristics of these kinds of interference depend on the traffic shape, as well as the radio channel behavior. We will see later that it's usual to model the bursty traffic by the aggregate traffic generated by a number of ON-OFF mini-sources with exponential distributions for ON and OFF periods. So it seems reasonable to model the interference as bursts with exponential or Gamma distributed inter-arrival times. As such the models presented previously for the Rayleigh fading can be extended to interference as well.

As we mentioned earlier, the attenuation is noticeable in the indoor environment. Thus, one may assume that the interference originated from communications in other area cells is low comparing to the multipath fading, especially if the area cells are surrounded by radiation absorbing walls. So, one may disregard the interference effects when the frequency reuse factor is not too low.

2.4.4 The Effect of Utilization on Interference

When the offered load increases the probability of a connection being interfered is higher. So the channel utilization (defined as the mean offered load divided by the available capacity) would have direct impact on channel behavior. To formulate the effect of utilization on the fade probability, we consider the interference as background additive noise [58]. Consider the memoryless thresholding in which the fade interval is detected by comparing the signal to noise ratio at the receiver with a certain threshold value. The probability of being in a fade is equal to:

$$p_{fade} = p\left(\frac{P_r}{N_T + I} < T_d\right) \quad (2.13)$$

N_T is the power of thermal noise and I is the power of interference. Considering the exponential distribution for signal power at the receiver, one can write:

$$p_{fade} = 1 - e^{-\frac{(T_d (N_T + I))}{\bar{P}_r}} \quad (2.14)$$

or:

$$p_{fade} = 1 - \xi e^{-\frac{I}{I_o}} \quad (2.15)$$

where:

$$\xi = e^{-\frac{T_d N_T}{\bar{P}_r}} \quad \text{and} \quad I_o = \frac{\bar{P}_r}{T_d} \quad (2.16)$$

Since CCI is usually assumed to add on a power basis [3], increasing the utilization results in a proportional increase in interference power. Therefore, equation (2.15) can be written as:

$$p_{fade} = 1 - \xi \cdot e^{-\frac{\chi \cdot \rho}{I_o}} \quad (2.17)$$

where ρ is the utilization, and χ is a coefficient which depends on some system specifications such as the frequency reuse factor, the size of the radio cell, the average transmission power, and the physical situation of the cell under study.

In the case that $\bar{P}_r \gg T_{th} \cdot I$, the exponential term in equation (2.17) can be expanded to:

$$p_{fade} = (1 - \xi) + \frac{\xi \cdot \chi}{I_o} \cdot \rho \quad (2.18)$$

which expresses a linear relation between the fade probability and the channel utilization.

2.5 Conclusion

In this chapter we addressed some issues in wireless indoor communications. The important conclusion is that the behavior of the radio channel can be modeled by two states: ON state and OFF state. In the ON state the transmission is error free, while in the OFF state the channel is useless. The major factors that determine the state of the channel are fading, shadowing and interference. The statistical characteristics of the channel are affected by the techniques which are taken to avoid channel failures, and to recover the failed channel. In addition to that the interaction between the channel and access method has noticeable effect on the channel model. The channel utilization may have a direct impact on the interference power and this effect may be considered as a linear relation between the channel utilization and the fade probability.

In the next chapters to analyze the system, we assume a general characteristics for the channel with this assumption that the channel conditions are independent in successive server visits to a user. In analysis, the channel behavior is characterized only by the average channel failure rate (CFR). However in simulations we assume an exponential

distribution for ON periods. Several possibilities will be tested for the OFF period characteristics.

Chapter 3

Polling Based Multiple Access Schemes

3.1 Introduction

The choice of a proper method for allocating the available bandwidth to the connected users depends on the type of supported services. The two extremes, are constant bit-rate traffic, and in the other side, bursty traffic. For the first case, the declared traffic parameters by the user, at the first attempt for establishing the connection, may be sufficient for bandwidth assignment, in a "pure reservation" fashion. However, for the second extreme, to govern the bandwidth efficiently, management on the "call level" is not sufficient. The controller needs to have access to short term traffic information, to carry on the control procedure on the "burst level" and "cell level" as well.

To support multimedia services in IBWN, the multiple access protocol should be based on the up-to-date information collected from the connected terminals. A polling scheme, modified to comply with wireless network necessities, seems to be capable to fulfil the above requirements. It offers the capability of supporting "bandwidth on demand" mode, with full control over the procedure. The controller can follow the sudden changes in bit-rate of the heterogeneous sources. The priorities can be preformed efficiently, and switching to higher or lower priorities within a call, can be supported. Regarding the above, in the following discussions, our approach for the access mechanism is based on the polling protocols.

In the following sections, we briefly explain the characteristics of the supported multimedia services, their requirements, and the modeling methods. Then, we investigate multiple access protocols based on the polling discipline.

3.2 Multimedia Services and Their Requirements

In general one can categorize the supported services in a multimedia terminal, to two basic categories: the real-time traffic (RTT), and the non-real-time traffic (NRTT). The basic difference between the two is that in RTT the receiver at the end of the path uses the signal immediately, thus, a long delay is not tolerated. In the following sections, other aspects of these two kinds of traffic are further discussed.

3.2.1 Real-Time Services

The important property of real-time connections is the small maximum transfer delay (MTD) requirement. Each transmitted cell in RTT has a time stamp, within which if the cell is not delivered to its destination (the deadline expires), the cell won't be useful anymore and has to be dropped. From the bit-rate variations point of view, the RTT sources may be of constant bit-rate (CBR) type, or variable bit-rate (VBR) type. The CBR sources generate a periodic stream of cells during a call, so that the bit-rate is constant, and the inter-cell interval is fixed, determined by the bit-rate. The bit-rate in a VBR source, changes in time, and most likely has bursty characteristics. The VBR sources may be:

- Sources such as voice with silence detection, which alternate between active period, emitting cells at constant rate, and silence period with no transmissions. These sources can be modeled using a single ON/OFF Markov process [13].
- Variable rate cell stream, such as output of VBR video coder, whose instantaneous rate changes rapidly as the content of the filmed scene changes.

The VBR mode for compressed video supported by ATM is of particular interest because of a number of potential technological benefits. The VBR is expected to be advantageous over the CBR both for the network and for the users interests. These advantages may be listed as the following [40,47,73,79,80]:

- Low latency/delay; when a network supports a CBR connection, a large buffer is required between the coder and the network to absorb the changes in bit rate generated in frames with different contents. Therefore, the buffering delay is much larger than that of the VBR algorithm. In CBR transmission, the end-to-end delay is the sum of the encoding delay, the buffering delay and the decoding delay. This delay for MPEG

(Moving Picture Experts Group) is something about 10.8 frames which corresponds to about 360 ms. This delay is larger than the tolerable delay for interactive applications, which is assumed to be about 150-300 ms. In VBR transmission the packetization delay should be considered instead of buffering delay. This delay in the worst case is about 1/15 frame which is about 2 ms, as explained in reference [47].

- Lower transmission and switching cost; due to resource sharing, and effective integrated transport for multimedia applications with fast bit-rate variations, the broadband networks reach a better utilization with VBR sources. Through statistical multiplexing, the network should be able to carry more VBR video calls than CBR video calls.

- Constant image quality; the user is expected to obtain better quality with VBR video than CBR, when both systems have the same average bit-rates.

In contrast VBR video is more susceptible to cell loss. This is because CBR video has generally more redundancy and therefore can tolerate more loss in coded data [40]. Also, since the CBR traffic is predictable, the traffic management for CBR connections is much easier than VBR ones.

For the above advantages, the video teleconferencing, MPEG and HDTV (high definition TV), originally coded by CBR methods [5,11,39], recently are considered as candidates for VBR coding techniques. Efforts have been done to propose VBR versions for MPEG and HDTV video transmissions [75,79,80,106]. But still, no general consensus has yet been reached on whether VBR schemes are better than CBR schemes for some of the video services [32]. Therefore, both VBR and CBR services may be requested, during a multimedia call. The modeling of CBR sources is a trivial issue, but VBR video modeling is subject of extensive studies, presented in the following section briefly.

3.2.2 Modeling of VBR Video

One of the main properties of bursty sources, such as VBR video, is the high correlation between consecutive arrivals. Two types of correlations are evident in the cell generation process of a video source: short term correlation and long term correlation. Short term correlation corresponds to uniform activity levels namely the small fluctuations in bit-

rates, and its effects last for a very short period of time (in the order of a few hundred milliseconds). Long term correlation corresponds to sudden scene changes which cause a large change in the rate of arrivals, and its effects last for a relatively long period of time (on the order of few seconds) [88]. A good model for a video coder has to consider and simulate both of these correlations.

Several models have been proposed for VBR video traffic. In general the parameters of the model are obtained by matching the first two moments of bit-rate or inter-arrival time of the model with the actual traffic.

VBR Video Modeling for Simulation Purposes:

A group of models use ARMA (auto-regressive moving average) process to describe VBR traffic. These models generally fit the data well in a statistical sense, but do not produce enough large values [32], and can not be applied in a tractable analytical study of the system, so they are basically used for simulations [61]. A simple model of this type uses a first order AR (auto-regressive) process with a Gaussian input to model the number of cells generated per frame of VBR video [61,73]. This model is proposed on the basis that the frame to frame bit-rate has a bell-shaped histogram, which can be approximated by Gaussian pdf. The coefficients of the AR process are determined by matching the average and autocovariance functions of the model and experimental data.

For the slow motion video teleconferencing where the sequence doesn't have scene changes or scene cuts, it has been found that the number of cells per frame follows a gamma (or negative binomial) distribution rather than Gaussian distribution [32]. [60] has obtained a better fit by Markov renewal process. The process contains 40 equidistant levels, and a mixture of two geometric distributions for the pdf of sojourn time of each level. In [112], full motion video traffic, coded by a motion-adaptive coder and MPEG, is modeled. A switched Gaussian distribution and a time-varying AR process are suggested to provide accurate models for generic full-motion scenes.

To capture the long term correlation [82] has proposed a Markov chain to switch between several AR models each one corresponding to a scene sequence with moderate motion. More complete model is proposed by [89]. This model consists of two complementary AR

processes of the three state Markov chain process. The first process is to capture the short term correlation of the bit-rate and the second is to keep track of the peaks observed during the scene changes. An important notification is that all of the above models in fact assume that the cells generated in a frame are buffered at the video coder output and then released to the link.

The model which is proposed by [25] does not assume frame buffering at the video coder output. Instead the number of cells, produced by the coder, in a block of 64 ATM cells duration is obtained. The model is again an AR process but to capture the correlation at this accuracy, a high order (325) transversal filter is used. They've obtained the coefficients of the filter using the measured autocovariance coefficients of the actual video traffic.

Another method which models VBR video for simulation purposes, is called TES (transform-expand-sample) method [64,41]. The model applies two random sequences. the first one which is samples of a uniform random variable (RV) in (0,1) interval, acts as the background sequence, and is used to model the first moment of the video traffic. The second one, which can be a general RV, combined with the first sequence, smoothed and filtered out, models the second moment of the video traffic. This technique can be utilized to model the VBR video traffic, at the block level as well as the frame level.

In [62], a multistage discrete-state Markov chain is used to model the aggregate video traffic, where each VBR-coded source is modeled by a renewal process. In this study, the average arrival rate and the square coefficient of variation of cell arrivals are used to approximate the parameters of the arrival process, and the dependency between successive frames is considered.

VBR Video Modeling for Analysis Purposes:

The second group of models, which are more useful for analytical works, estimates the aggregate video traffic by a renewal process for the inter-arrival times [63], or multi stage birth and death process for the bit-rate [61,88,92,110]. With a detailed Markov chain (enough large number of states) these models perform very well and are good models for traffic studies [32]. In [61], the model is a one dimension multi stage birth and death

process with fixed bit-rate in each state. This model doesn't consider the effect of scene changes. To capture both, the short and long term correlations, a two dimension Markov chain is proposed. One dimension corresponds to the short term correlation and the second dimension, with bigger jumps in bit-rate, corresponds to scene changes [88]. In general, an N stage birth and death Markov chain, can be considered as the superposition of N ON-OFF, two states, Markov mini-sources [57,4]. In the model proposed by [110], the cell arrival process from a single video source is modeled as discrete state continuous time markov process with batch arrivals representing scene changes. The interval times between scene changes (batches) are assumed to be exponentially distributed, and the batch size is assumed to be constant.

3.2.3 Non-Real-Time Services

In contrary to the RTT, the NRTT is more tolerable to delay, but usually has more stringent cell loss probability requirement. The NRTT may be modeled by Poisson or Bernoulli process, when the data is packetized and sent through the link without correlation between inter-arrival times. But in a broadband network with ATM cell size data units, it's more likely that the cells are produced tetherly [81]. If the application can tolerate considerable delay, such as electronic mails, it's possible that the cells are buffered at the source and then released to the link gracefully (traffic shaping). This procedure leads to constant bit-rate or smooth traffic shape.

For those services where traffic shaping delay is not endurable, like document retrievals or still images, the cells are produced and transferred in bursts. Such sources may be modeled by interrupted (Markov modulated) Bernoulli processes (IBP or MMBP). The Markov process has two states, an active state and an idle state. The duration of each state is geometrically distributed with different parameters. The process remains in active(idle) state with probability p (q), and changes to alternative state with probability $1-p$ ($1-q$). Arrivals occur in a Bernoulli fashion (with probability a) during the active state, and no cell is produced during the idle state. Maximum burstiness is achieved when every slot contains a cell, during the active period ($a=1$ for the Bernoulli process), which is in fact the ON-OFF (birth and death) Markov process [43]. The aggregate traffic of several data sources may be modeled by Markov modulated Poisson process (MMPP).

3.2.4 Multimedia Traffic Modeling

From the previous discussions, one can conclude that all kinds of sources in ATM multimedia, can be modeled by superposition of proper number of identical ON/OFF Markov mini-sources (figure 3.1). The ON and OFF periods of a mini-source are geometrically distributed, where during the ON state, it generates ATM cells at its peak-rate (PR) constantly. The percentage of the time that a mini-source is in ON state is called the activity ratio (AR). The number of mini-sources (M), the averages of ON and OFF periods (T_{ON} and T_{OFF}), and the bit-rate during the ON state, are important parameters and have to be determined carefully according to the actual traffic parameters. Improper values for those parameters bring about false estimation of the network performance [115,57].

In [54], typical values for the model parameters of some multimedia sources are given. For instance, a voice call with silence detection, can be modeled by:

$M=1$ mini-source, with $PR=64$ kbps or 32 kbps,

$AR=0.4$ to 0.5 (0.35 for ADPCM voice),

$T_{ON}=1.2$ sec ($.35$ sec for ADPCM voice).

The VBR encoder output of a CATV source, has a bit-rate ranging from 0 to 44.1 Mbps, with an average at 16.8 Mbps [106]. It can be modeled by:

$M=30$ mini-sources, with $PR=1.47$ Mbps,

$AR=0.38$, and $T_{ON}=0.033$ sec.

The video conferencing with 1 Mbps peak-rate, can be modeled with following parameters:

$M=15$ mini-sources, with $PR=66.7$ kbps,

$AR=0.32$, and $T_{ON}=0.033$ sec.

Figure 3.1 shows the output of a VBR video source which is modeled by aggregate traffic produced by 15 ON-OFF mini-sources, each one with 0.25 activity ratio, mean ON

duration 33 msec. The source mean bit rate is 1.1 Mbps, the link capacity is 14 Mbps, and the frame duration is 33 msec.

3.2.5 Traffic Requirements for Multimedia Services

Some of the expected services to be offered by a multimedia terminal in broadband networks, are listed in table 3.1, taken from the references [2,20, 22,39,50,55,74]. It can be observed that the requirements of the listed services are very diverse. As we mentioned earlier the real-time applications are mostly sensitive to excessive transmission delay, especially interactive ones, while non-real-time applications have very low cell loss tolerance.

3.3 Polling Based Multiple Access Protocols

3.3.1 Cyclic Polling Systems

The basic model for the polling system, consists of N infinite size queues and a single server (in general multiple servers) which serves them one at a time. The model has been treated both in a continuous-time and discrete-time framework which are equivalent in most of the aspects [97]. Several service policies have been examined and studied in the context of polling systems. The most common ones are the *exhaustive*, *gated*, and *limited* policies.

In the exhaustive service discipline, the server serves queue i until the queue is empty, then departs for the next queue in sequence. The gated policy rules out in a way that, server serves only the jobs presenting in the queue at the polling instant. In limited scheme, a limited number of jobs are served by the server in each visit to the queue. If at most one customer is served in each visit to the queue, the discipline is called *limited-1* or *non-exhaustive*. When limited number but more than one customer are to be served in each visit to a queue, if the service is in exhaustive manner, meaning that while visiting queue i , the server works until either the limit is met, or the queue becomes empty, the policy is called *E-limited*. If the server encounters l_i jobs upon arriving to queue i , and serves the maximum of the limit and l_i (the limited scheme in gated manner), the policy is called *G-limited*. While the exhaustive method is found to offer the best efficiency among

Figure 3.1 The output of a VBR video modeled by aggregate traffic produced by 15 mb/s sources

TABLE 3.1 Requirements of typical multimedia services

<i>Service type</i>		<i>Burstiness</i>	<i>Burst duration</i>	<i>Required bandwidth</i>	<i>Maximum cell loss</i>	<i>Maximum transmission delay</i>
Real Time	VBR(CBR) Voice	5-15 (1)	1 sec	16 -256 kbps	$10^{-4} - 10^{-6}$	150-250 ms
	VBR(CBR) Video Telephony	2-5 (1)	30-100 ms	64 kbps	$10^{-4} - 10^{-6}$	150 - 350 ms
	VBR(CBR) Video-conferencing	2-5 (1)	30-100 ms	64-320 kbps	$10^{-4} - 10^{-6}$	150-350 ms (jitter 5ms)
	VBR(CBR) MPEG NTSC Video	2-5 (1)	33 ms	1- 4 Mbps	$10^{-4} - 10^{-6}$	40 ms (jitter 5ms)
	VBR(CBR) HDTV NTSC Video	2-5 (1)	33 ms	20 - 150 Mbps	$10^{-4} - 10^{-6}$	40 ms (jitter 5ms)
Non-Real Time	File Transfer Electronic Mail	1	1 sec	9.6 kbps - 2 Mbps	10^{-9}	10 - 100 sec
	Medical X-ray Still Image	25 (1)	1 sec	1 - 10 Mbps	$10^{-9} - 10^{-12}$	1 - 5 sec
	Document Retrieval Data or Demand	40 - 200	40 - 250 ms	64 kbps 5 Mbps	$10^{-9} - 10^{-12}$	1 - 3 sec

polling schemes in terms of the overall mean waiting time or unfinished work, the limited-1 discipline is the best in terms of fairness [99,21,17].

There are other modified types of polling, among them is the *adaptive polling*, in which the limit on the number of served jobs of each queue in each visit is determined regarding the traffic parameters and the buffer contents[48].

The above methods may be considered with *finite buffer capacity*, in which instead of infinite queues lengths, the queue buffers are able to store only one job (*single queue*) or a limited number of jobs. When the queue is full, the excessive jobs (low priority ones based on the service discipline) would be dropped.

3.3.2 Previous Works in Polling analysis

The polling system in wired (perfect link) networks has been the subject of numerous studies in the last two decades, triggered when it was used to model time-sharing computer systems, in the early 1970's [56]. A tutorial on polling schemes, their analysis methods, and their comparative performances, can be found in Takagi's works [96,97,98,99], and also [108], and [56]. More recent works has been devoted to finite capacity polling systems, for limited-1 service discipline in [103], and for gated, limited, and exhaustive systems with dependency assumption between the vacation times (the time in which the server doesn't serves the interested queue) and the busy periods in [53]. Approximations for mean waiting times for limited services are obtained in [21] and [93].

Polling with Bursty Arrivals:

A basic assumption in all the above mentioned works is the independent Poisson arrivals. But the Poisson process is not able to convey the fundamental property of bursty traffic, which is the short or long term correlation in cell arrival rate. As it has been stressed out [95,62], if the correlation between arrivals, is not considered in queue analysis, a noticeable false estimate may occur in network performance, delay and loss calculations. For that reason, few recent works have focused on evaluating polling efficiency, considering the bursty arrivals. One work in this area, reported in four papers [43,44,45,46], has analyzed a discrete-time, limited-1, polling system with finite buffer capacity, under bursty arrival process. The symmetric work load, and zero switch-over

time, are assumed. The polling system is approximated by an ATM multiplexer and analyzed on that basis. In another work, finite capacity, limited-l, discrete polling system with blocking, is considered [113]. The arrivals are assumed to be bursty with Bernoulli interrupted model. The authors have employed a numerical-analytical approximation algorithm to study the output queue of the multiplexer.

Polling in Wireless Networks:

Most recently, some investigators have considered versions of polling for multiplexing mixed traffic, mostly data and voice packets, on the indoor wireless networks [10,67,33,29,117,118]. A modified polling strategy [117,118] has been utilized in a 5 Mbps indoor LAN, in which the portables are small "notebooks" able to produce relatively low bit-rate voice and data traffic. The base station polls all the remotes at the beginning of each limited polling cycle. The remotes may response by a request or a short "keep alive" packet, by which the base adjusts the weights of its phase array antenna. After polling all the remotes, and getting the responses, the base first takes care of any remained packet from the last cycle, then starts to response to the currently polled remotes using some service discipline. Getting the chance, the remotes send the packets out, unless the limit on the total cycle length is met. Being so the base stops the cycle and begins a new cycle by polling remotes again. So basically, the scheme is exhaustive, except that the base cuts the cycle off, if it exceeds the cycle time limit. The performance of the system is evaluated analytically, disregarding the possible channel impairments, and delay restrictions. For a polling cycle limit of 20 ms, 10 to 50 number of users and Poisson arrivals, the maximum link efficiency (maximum utilization) is found to be 97% and 87% respectively.

3.4 Analysis of the Gated Polling with Bursty Arrivals

In this section we present an original work on the analysis of the gated polling, with bursty, correlated arrivals in the radio environment. Then we evaluate the performance of this method for a mix of bursty traffic types.

3.4.1 Assumptions

We consider only one radio cell, which is served by a single base station connected to a wired backbone broadband local area network. The synchronization between the base station and remote terminals is assumed to be perfect. During this study, only the uplink traffic (from terminals to the base) is considered. The channel failure, whenever happens, is assumed to last no more than a cycle. This assumption is valid, since reasonably there exist a mechanism to detect and mitigate the fade for the next cycle. The ARQ is applied in which the erroneous cells are retransmitted in the next cycle. We assume that the time is slotted to ATM cell size. The departure process is deterministic unless the channel failure happens. Each source is modeled as a set of identical and independent ON-OFF mini-processes, and the arrival process is the superposition of the output of M independent sources. The system is studied under fixed configuration of connected sources, meaning that there is no connection establishment or termination. Assuming stationarity, we study the system in the steady state conditions.

3.4.2 Arrival Process Characteristics

The cell arrival process of each source is assumed to be the superposition of proper number of independent ON-OFF mini-sources as shown in figure 3.2. If a mini-source is in ON state, it remains there in the next slot with probability p , and switches to OFF state with probability $1-p$. Similar phenomena happens when the mini-source is in OFF state (with probability q). So the process can be described by the following transition matrix:

$$T = \begin{bmatrix} p & 1-p \\ 1-q & q \end{bmatrix} \quad (3.1)$$

and the probabilities of being in each of the states, in the steady state, are given by:

$$\pi_{ON} = \frac{1-q}{2-q-p} \quad (3.2)$$

and:

$$\pi_{OFF} = \frac{1-p}{2-q-p} \quad (3.3)$$

Figure 3.2 The ON-OFF Markov mini-sources model for VBR traffic

The mean of the process, which is the probability of producing a cell in a time slot is equal to:

$$\bar{\epsilon} = \frac{1-q}{2-q-p} \cdot \gamma \quad (3.4)$$

where γ is the cell-rate during the ON state.

Since the peak cell rate of each mini-source is less than the link capacity, the variance of cell arrivals is as the following (for a Geometric distribution):

$$\sigma_{\epsilon}^2 = \frac{(1-q)\gamma}{2-q-p} - (\bar{\epsilon})^2 \quad (3.5)$$

Assuming that the source j consists of M_j independent, identical mini-sources, each one having p_j and q_j parameters and producing γ_j cells during a time slot (ATM cell size) in the ON state, the autocorrelation of the cell arrivals, $R_j(n)$, is defined as:

$$R_j(n') = E \{ (\mu_j(n) - \bar{\mu}_j) \cdot (\mu_j(n-n') - \bar{\mu}_j) \} \quad (3.6)$$

where $\mu_j(n)$ is the number of cell arrivals for remote j at time slot n .

Assuming that the ON duration is much larger than a time slot, $R_j(n)$ is given by:

$$R_j(n) \approx \begin{cases} M_j \cdot \sigma_{\epsilon}^2 & n = 0 \\ -(\bar{\mu}_j)^2 & 0 < n < \left\lfloor \frac{1}{M_j \cdot \gamma_j} \right\rfloor \\ \frac{M_j(1-q_j)\gamma_j}{2-q_j-p_j} \cdot (p_j)^{\left\lceil \frac{1}{\gamma_j} \right\rceil \cdot k} - (\bar{\mu}_j)^2 & n = \left\lfloor \frac{1}{M_j \cdot \gamma_j} \right\rfloor \cdot k \\ 0 & \text{elsewhere} \end{cases} \quad (3.7)$$

where $\lfloor \cdot \rfloor$ is the floor function, returning the nearest integer smaller than its argument, $\lceil \cdot \rceil$ is the ceiling function, returning the nearest integer larger than its argument, $k = 1, 2, \dots$, and $\bar{\mu}_j$ is the mean cell arrival rate or the probability of having a cell in a time slot, and is equal to:

$$\bar{\mu}_j = \frac{M_j \gamma_j \cdot (1 - q_j)}{2 - q_j - p_j} \quad (3.8)$$

The autocorrelation function of a typical source (MPEG VBR video, with 1.65 Mbps average bit-rate), consisting of 20 mini-sources, each one with 0.375 activity ratio, and 0.033 sec for mean ON duration, is shown in figure 3.3.

3.4.3 Characteristics of the Queue Length at the Polling Instant for the Gated Polling System

Defining C_i as the number of slots in the i th polling cycle, and S_i as the overall polling overhead in that cycle, for the assumed system one can write:

$$C_i = S_i + \sum_{j=1}^N W_{i,j} \quad (3.9)$$

where N is the number of communicating remotes, and $W_{i,j}$ is the number of the slots allocated to user j during the cycle C_i , which is equal to the number of jobs presenting at the user's queue at the polling instant, and is given by:

$$W_{i,j} = \zeta_{i-1,j} + \sum_{n=1}^{C_{i-1}} \mu_{i-1,j}(n) \quad (3.10)$$

where $\mu_{i-1,j}(n)$ is the cell arrival rate for remote j at time slot n , during the polling cycle $i-1$, and $\zeta_{i-1,j}$ is the number of the slots which are not available to remote j due to channel failure during the $(i-1)^{th}$ cycle. The above equations result from both effects of the cells stored in the remotes buffers during $(i-1)^{th}$ cycle, and the erroneous cells during that time have to be transmitted in the i^{th} cycle. Thus, the i th cycle time is the time needed to transmit those cells, plus the polling overhead.

As we noted in chapter 2, while communicating with the base, the remotes experience different radio channels. Defining CFR_j as the average channel failure rate for remote j , the mean number of allocated slots to user j ($\bar{W}_j$) can be obtained as (see appendix A, section A.1, for details):

Figure 3.3 The autocorrelation function for a typical VBR source modeled by ON-OFF sources

$$\bar{W}_j = \frac{\bar{C} \cdot \bar{\mu}_j}{1 - CFR_j} \quad (3.11)$$

where $\bar{\mu}_j$ is the mean cell arrival of the j th source during a time slot.

In this study we consider a single radio cell in isolation, thus the effect of interference is disregarded. As such the channel failure is due to fading and shadowing only, so CFR_j is independent from utilization. Therefore the mean cycle time, $\bar{C}$, is equal to (appendix A.1):

$$\bar{C} = \frac{\bar{S}}{1 - \rho'} \quad (3.12)$$

where $\bar{S}$ is the total mean overhead (which can be polling and responses, guard times, etc.), and:

$$\rho' = \bar{\zeta}_p + \rho \quad (3.13)$$

where ρ is the total utilization (the probability of having a new cell in a time slot from any of the connected remotes). $\bar{\zeta}_p$ is the percentage of erroneous cells due to channel failure, during a cycle, and is equal to:

$$\bar{\zeta}_p = \sum_{j=1}^N \frac{\bar{\mu}_j \cdot CFR_j}{1 - CFR_j} \quad (3.14)$$

The system is stable if the following inequality holds:

$$\rho' < 1 \quad (3.15)$$

When all the remotes experience equal channel failure ratio ($CFR_j = CFR$), we will have:

$$\rho' = \frac{\rho}{1 - CFR} \quad (3.16)$$

$$\bar{C} = \frac{\bar{S}(1 - CFR)}{1 - \rho - CFR} \quad (3.17)$$

$$\overline{W}_j = \frac{\bar{S} \cdot \bar{\mu}_j}{1 - \rho - CFR} \quad (3.18)$$

Fulfilling stability requirement (equation (3.15)) results in:

$$\rho < 1 - CFR \quad (3.19)$$

Equation (3.19) simply means that, the total utilization should be less than the available channel capacity, considering the channel failures.

Using equation (3.10), the variance of $W_{i,j}$ is obtained as:

$$\sigma_{W_i}^2 = \sigma_{\zeta_i}^2 + \sigma_{\vartheta_i}^2 + 2R_{\zeta_i \vartheta_i} \quad (3.20)$$

where $\sigma_{\zeta_i}^2$ is the variance of the channel failure, and $\sigma_{\vartheta_i}^2$ is the variance of $\vartheta_{i-1,j}$, which is defined as:

$$\vartheta_{i-1,j} = \sum_{n=1}^{C_{i-1}} \mu_{i-1,j}(n) \quad (3.21)$$

and $R_{\zeta_i \vartheta_i}$ is the correlation coefficient between $\zeta_{i-1,j}$ and $\vartheta_{i-1,j}$. All of the terms are obtained in appendix A.2.

The above equations illustrate the effects of the channel failure, as well as the burstiness of the input traffic on the variance of the buffer occupancy. The correlation between cell arrivals has a direct impact on the variance of the cycle time and the variance of the user's buffer occupancy at the polling instant.

3.4.4 Overflow Probability for the Gated Polling System

As it's shown in figure 3.4, Overflow most likely happens during the instances before the beginning of the service time. The reason is that before the service is given to user j , the buffer occupancy is monotonically increasing. During the service time, since the link capacity is exclusively available to the user j , and the arrival rate of a single user is normally much less than the link capacity, the queue length is monotonically decreasing. So the highest buffer occupancy happens at the instant before the beginning of the service time. Therefore, for very low overflow probability (less than 10^{-4}), it seems to be a good

Figure 3.4 Graphical model of the buffer occupancy variations during a cycle time for one user

approximation, if one only consider the probability of overflow at the polling instants. Furthermore the overflow probability can be considered as a good approximation for the cell loss probability when the cell loss probability is very small.

The VBR, bursty traffic is modeled by a set of independent ON-OFF mini-sources. Considering one slot, a mini-process is in ON or OFF state, which is a Bernoulli trial. Therefore, the whole arrival process in a time slot, is the superposition of independent Bernoulli trials, which can be modeled by a Gamma distribution, when the number of the trials is relatively high [76]. From equation (3.10), it can be noticed that, the buffer occupancy at the polling instant, can be considered as a combination of a number of processes which each one may consist of several ON-OFF sources, thus one may model it as a Gamma process. The pdf of a Gamma process is completely specified in terms of the mean and variance of the process. The mean and the variance of $W_{i,j}$ at the polling instant are given by the equation (3.10), and (3.11). Using these mean and variance, we found the pdf of the buffer occupancy at the polling instant, and from there, we estimated the overflow probability.

3.4.5 Simulation Results

To verify the analysis, a simulation has been done with the following assumptions:

Sources types are as follows:

1-four sources with 1.5 Mbps average bit-rate (e.g. MPEG VBR video), which goes to $1.1 \times 1.5 = 1.65$ Mbps considering the ATM cell overhead. Each source is modeled by 20 ON-OFF sources, with 0.375 activity ratio, and 0.033 sec for mean ON duration.

2-twelve sources with 320 kbps average bit-rate (e.g. VBR video conferencing), going to 352 kbps considering the ATM cell overhead. Each source is modeled by 15 ON-OFF sources with 0.32 activity ratio and 0.033 sec mean ON duration.

The link capacity is 12 Mbps. The channel parameters are considered to be the same for all the sources. The link fails in 1% of the times, and the OFF duration is modeled as exponential distribution with 10 ATM cells mean. The gated scheme is applied, and the polling overhead is assumed to be 3 ATM cells per user, in each polling cycle. The simulation is done for 2×10^6 ATM cells, corresponding to 70 seconds.

The results of the simulation are as following:

- As it illustrated in figure 3.5, the pdf of $W_{i,j}$ fits well to the Gamma distribution, especially in the tail of the pdf, for both of the source types.
- The simulation and analysis results are compared in table 3.2:

TABLE 3.2 Comparison between simulation and analysis, for gated polling with bursty arrivals

Source Type	Source 1		Source 2	
	$\overline{W}_j$	σ_w^2	$\overline{W}_j$	σ_w^2
Simulation	74	1325	15	82
Analysis	75	1205	16	75

The results show acceptable agreements between the simulation and the analysis.

For the above example the mean and the variance of $W_{i,j}$, versus the total utilization are illustrated in figure 3.6. Figure 3.7 shows the probability of having overflow when the buffer size is 117 ATM cells (30 ms mean delay) for the source type 1, and 83 ATM cells (100 ms mean delay) for the source type 2. The mean and variance of the buffer occupancy increase dramatically as utilization gets close to its maximum value. An overflow probability equal to 10^{-4} , is not reachable for source type 1, even under 70% utilization.

This study shows that the non-limited polling presents poor performance for bursty traffic, when the delay constraint is stringent. Moreover, since the problem returns to the property of being "non-limited", this conclusion can be generalized to other methods which do not impose any limit on the allocated slots to the connected users.

3.5 Conclusion

The first sections of this chapter was appropriated to multimedia services, their modeling methods, and their requirements. The multimedia traffic can be a heterogeneous mix of real-time and non-real-time traffic. The traffic characteristics and the QOS requirements are very diverse. The MTD may vary in the range of 30 msec to couple of seconds and the

Figure 3.5 Comparison between Gamma distribution and The pdf of the buffer occupancy at the polling instant, (a) the source type 1, (b) the source type 2

Figure 3.6 The mean and variance of buffer occupancy at polling instant vs. the utilization. (a), (b): the source type 1, (c), (d): the source type 2

Figure 3.7 The overflow probability for two types of traffic vs. total utilization

tolerated cell loss rate may be ranged from 10^{-4} to 10^{-12} . The immediate conclusion is that the access method must consider traffic properties and requirements, otherwise the system performance would be very deficient.

In the rest of the chapter, the polling multiple access alternatives were briefly explained. The polling based schemes in the context of broadband wireless networks were our interest. We analyzed the gated polling system with bursty arrivals mathematically and by simulations, and showed that unlimited schemes offer poor performance due to unfairness toward sensitive to delay sources.

In the next chapter we propose a multiple access scheme based on limited-G polling discipline, and show that acceptable performance can be achieved using limited service discipline along with proper methods to improve the efficiency of the system.

Chapter 4

Limited Polling Based Protocols for ATM-IBWN

4.1 Introduction

In the previous chapter we showed that the non-limited gated polling scheme, meets the requirements of bursty, delay sensitive sources, under very low utilization. In this chapter first we describe briefly, the basic elements of a traffic controller for an ATM network, then propose and investigate a limited-polling base multiple access scheme for the multimedia ATM indoor wireless LANs.

4.2 Bandwidth Management in ATM Networks

In multimedia communications a wide range of services, with different traffic behaviors and requirements share the same ATM transport. To control this complex mix of traffic in high speed ATM networks, fast and efficient algorithms with low processing times are required. So many of the bandwidth management schemes developed for low speed, homogenous traffic, may not be applicable to ATM networks [109].

The bandwidth controller for broadband ATM networks should satisfy three objectives:

- 1- Efficient utilization of the network capacity and resources. While utilizing the resources at the highest level, the controller should be able to avoid any congestion occurrence leading to a drop in total throughput
- 2- Satisfying the QOS (Quality Of Service) requirements such as connection blocking probability, cell loss rate, and transfer delay for all the supported traffic types, assuring that sufficient network resources are available for each admitted connection

3- Providing fair access to the network resources for all types of connections and services, and also fair degradation in service quality, when the aggregate traffic load is close to the available capacity [49].

4- Universality of the ATM layer over all types of interconnected networks, thus simplifying the interfaces and interconnections

A fair bandwidth allocation procedure is characterized by the following properties:

- no one receives more than what he is able to use,
- the resource is completely used, unless some remains after everyone receives the full amount he needs,
- if the available resource is not as much as all the users need, everyone receives less than he needs, as much as the others.

The mentioned goals may be followed by some procedures which are described in the following sections [4,36,104,109].

4.2.1 Statistical Multiplexing

Statistical multiplexing is performed to allocate a bandwidth less than the peak bit-rate to the bursty sources while satisfying their service requirements. Statistical multiplexing may be applied in the following ways:

- **Compound multiplexing:** in which the supported services are grouped in classes and statistical multiplexing is used inside each class. The classes of connections are defined on the basis of the traffic descriptors and QOS requirements. The controller segregates the total bandwidth and output buffer capacity available for each class, and performs independent control procedure for each class (Class Related Rule (CRR)). This method may offer a good compromise between efficiency and complexity [22,72,104]. The disadvantage is that controlling the different classes separately, restricts the flexibility of the overall control procedure in handling the cell loss and delay priorities, and more efficient use of the available bandwidth.

- **Full multiplexing:** in which unsegregated multiplexing is applied. In this case, the maximum gain may be obtained, and cell loss and delay priorities can be applied in favor of more sensitive sources [78]. But some drawbacks may occur due to the complexity of the control procedures and the modality of adding new services. For a bursty source, the traffic control overhead is more than a well behaving source. So performing the same management scheme for all types of traffic results in a rather inefficient control procedure.

4.2.2 Fair Bandwidth Allocation

Several techniques have been proposed for bandwidth allocation. The main objectives of these techniques are fulfilling the client requirements, and providing fair performance for all different services. To achieve fair performance for the bursty sources, some traffic descriptors which reflect the burstiness have to be used in the resource allocation policy. Beside the average bit-rate of the source and channel characteristics, some other parameters such as peak bit-rate, variance to mean ratio, average burst length, burst factor (the average number of cells accumulated in the buffer during a burst), the required coefficient of variation of the inter-arrival times, should somehow be taken into account. The authors of [4] believe that more than one parameter may be necessary to describe burstiness. In the following, some of the methods for bandwidth allocation in ATM networks are briefly described.

Equivalent Capacity Method:

One common approach to bandwidth allocation is to determine how much bandwidth a single source (or a class of sources) needs to satisfy its QOS requirements. This is referred to as “equivalent capacity” or “virtual bandwidth” [14,26,27,66,89,105,116]. Some of the works in this area present analytical expressions for computing the equivalent capacity required for a given type of connection. The expression for the equivalent capacity should be relatively simple, since it must be recomputed upon the addition or termination of a connection. The expression may depend only on the statistical characteristics of the source [105], or the statistical characteristics and the QOS requirements of the source and some characteristics of the network such as buffer size and the traffic load [27,66,89,116]. The required bandwidth may be evaluated considering the loss or delay requirements at the

cell-scale and burst-scale [2,37]. Using the burst-scale components, one may achieve more robust control over the burst arrivals [66,89].

A similar approach to the equivalent capacity, is the QOS evaluation method. In this method the highest level of QOS (e.g. cell loss probability) which can be supported by available resources are evaluated. The bandwidth is assigned considering the QOS requirements, and the call is admitted if the available capacity can guarantee the required QOS [37,69,83,84].

Pre-computed Maps Method:

Some of the investigators have proposed the use of a set of off-line pre-computed maps, through simulation or analysis, as the guideline for resource allocation. The maps are obtained under certain assumptions for the offered load and may be extended to general situations. The implementation of these proposals may require some amount of memory to store the resource allocation guidelines at the controller [15,22,38,107].

4.2.3 Traffic Shaping

The traffic shaping is smoothing out the large bursts by buffering them. Suppressing the bursts in this way imposes extra delay on the buffered cells. This degradation in the service quality may not be tolerated by some delay sensitive applications such as interactive video. But for bursty data sources which are more tolerant to delay, traffic smoothing can reduce the probability of congestion occurrence due to the bursts aggregation [24,36].

4.2.4 Anomaly Prediction

In this method the long-term burst aggregations are predicted using the traffic parameters. The reference [1] has modeled the traffic by Gaussian and Poisson distributions and then by utilizing the upper bounds on cell loss rate, regulations for congestion prediction have been obtained. Based on these regulations the admission policy has been proposed. Some other papers have used the learning ability of neural networks to identify the situations in which the anomaly happens, and then predicting and avoiding the congestion using the learned rules [51,71].

4.2.5 Other Methods for Bandwidth Management in ATM Networks

Other methods, which help to manage the bandwidth more efficiently, are: priority scheduling in favor of more sensitive to delay sources to avoid short term congestion [9,35], more robust error correcting coding for more sensitive to loss sources, backward congestion notification to source, forward congestion indication to destination [104], and considering the temporal behavior of the network and short time cell loss probability for bandwidth allocation, and call acceptance [4].

4.3 Limited Polling Alternatives

In this section we consider and study the limited polling based methods for the access mechanism in indoor broadband networks.

4.3.1 Choice Between Limited Polling Schemes

The versions of limited polling can be categorized to exhaustive-limited (E-limited), gated-limited (G-limited), and limited-1 (or nonexhaustive) schemes. As stated in previous chapter the limited-1 offers the least performance among the three. Limited-1 discipline requires fast switching between connected remotes, which may be difficult in radio environment. Moreover there have to be some overheads in each multiplexing frame for radio signalings and connection adjustments, therefore very small frame duration results in a low utilization and is not beneficial. So the limited-1 polling scheme seems not to be suitable for wireless networks.

In a G-limited scheme, the server may serve the queues right after polling instant, this is called *partially gated* system. Another possibility is that the server polls all the queues at the beginning of each cycle, during which the users request the slots as much as they need to empty their buffers, up to their service limits. Then the server gives the service to the queues in the order which they have been polled. This scheme is called *the fully gated limited (FGL) polling* [6]. The advantage of the FGL polling is that the controller has complete information about all the queues contents, and is able to perform more optimized bandwidth management. For instance, it may so happen that at the polling instant some of the queues have more cells than what their limits allow them to transmit, while some other

queues contain less cells than their limits, so that the total number of the cells is less than the cycle limit. In such a case for the E-limited and the G-limited schemes, some of the users are not allowed to empty their buffers while the cycle time is less than the target limit. But in the FGL polling, the controller can give permission to the queues to transmit their contents, as long as the total requested service is less than the cycle limit.

4.3.2 Random Polling

In the FGL scheme the order of visiting is important. The first polled queue gets the service right after polling duration at the beginning of each cycle, while the j^{th} queue has to wait until the service for the previous $(j-1)$ queues is completed. Therefore, if the order of the polling is fixed, depending on how later a queue is served, there would be a longer delay between its polling and service instants. To provide equal condition for all the queues, one may change the polling order in every cycle, so that every user has equal chance to get the first positions. The idea of "random polling", is providing fairness in polling order, regarding the traffic priorities [52].

In the radio environment, randomly changing the polling order, is beneficial in terms of dispersing the interference happenings among the remotes. Suppose that a strong signal from another nearby area cell, with the same frequency band, is interfering into the communications in the concerned area cell. Since the base stations are assumed to be synchronized, the interference more likely happens frequently in certain slots. In such a situation, if the polling order is fixed, the probability of having erroneous slots is higher for one of the remotes. Randomizing the polling order, shares the interference probability among all the users.

4.4 Analysis of the FGL Polling Scheme

In this section we present a mathematical analysis for the FGL polling systems.

4.4.1 Terminology

Figure 4.1 roughly shows the buffer contents of remote j during a multiplexing cycle. Suppose that at the polling instant in cycle i , the base station finds $V_{i,j}$ cells in j^{th} queue.

Figure 4.1 The buffer occupancy variations during a cycle time, for one user in a G-limited polling system

During the service time, all of these cells up to the service limit, k_j , would be served. If $V_{i,j} > k_j$, some of the cells found at the polling instant, would be left for the next service time. So denoting the number of served cells during cycle i by $W_{i,j} = \text{Min}(k_j, V_{i,j})$ and the unfinished work at the end of service time by $U_{i,j}$, one can write:

$$U_{i,j} = V_{i,j} - W_{i,j} \quad (4.1)$$

Having $U_{i-1,j}$ as the unfinished work in cycle, $i-1$, the server finds $V_{i,j}$ cells in the queue j at the polling instance of cycle i , so that:

$$V_{i,j} = U_{i-1,j} + \left(\zeta_{i-1,j} + \sum_{n=1}^{C_{i-1}} \mu_{i-1,j}(n) \right) \quad (4.2)$$

where $\mu_{i-1,j}(n)$ is the cell arrival rate for remote j at time slot n , during the polling cycle $i-1$, and $\zeta_{i-1,j}$ is the number of the slots which are not available to remote j due to channel failure during the $(i-1)^{\text{th}}$ cycle.

The cycle time is equal to sum of all the service times plus the polling overhead so:

$$C_i = S_i + \sum_{j=1}^N W_{i,j} \quad (4.3)$$

where C_i is the number of slots in the i^{th} polling cycle, and S_i is the overall polling overhead in that cycle.

4.4.2 Mean Cycle Time Analysis

Assuming the steady state, and taking the mean value of the above equations, lead to:

$$\bar{U}_j = \bar{V}_j - \bar{W}_j \quad (4.4)$$

$$\bar{V}_j = \bar{U}_j + \bar{\zeta}_i + \bar{C} \cdot \bar{\mu}_j \quad (4.5)$$

using the above equations, one can write:

$$\bar{W}_j = \bar{\zeta}_i + \bar{C} \cdot \bar{\mu}_j \quad (4.6)$$

Considering one single radio cell in isolation, the mean cycle time and mean service time can be obtained by the same methods as chapter 3:

$$\bar{W}_j = \frac{\bar{C} \cdot \bar{\mu}_j}{1 - CFR_j} \quad (4.7)$$

$$\bar{C} = \frac{\bar{S}}{1 - \rho'} \quad (4.8)$$

where again, CFR_j is the “channel failure ratio”, $\rho' = \bar{\zeta}_p + \rho$, and $\bar{\zeta}_p$ is equal to:

$$\bar{\zeta}_p = \sum_{j=1}^N \frac{\bar{\mu}_j \cdot CFR_j}{1 - CFR_j} \quad (4.9)$$

ρ is the channel utilization defined as the ratio between the total offered load and the available capacity.

4.4.3 Optimum Cycle Time Limit

The limit on the cycle time is imposed by delay requirements of the most stringent source, or some considerations of the radio link as pointed out in chapter 2. A cycle time beyond that limit produces lower system performance due to cell loss increase for bursty sources with low MTD requirements. On the other hand, for a given mean cycle time, the maximum utilization which is supported by the system, is obtained as:

$$\rho_{max} = 1 - \frac{\bar{S}}{\bar{C}} - \bar{\zeta}_p \quad (4.10)$$

To increase maximum affordable utilization, the $\frac{\bar{S}}{\bar{C}}$ should be small, so $\bar{C}$ should be as large as possible. The compromise between the above two confronting requirements gives an optimum value for the cycle time limit, under which the system reaches its highest performance.

4.5 Simulation Study of FGL Polling

A detailed simulation has been performed to study the performance of FGL polling discipline for controlling the multimedia traffic in an ATM indoor wireless network [68].

4.5.1 Simulation Assumptions

The focus of the study is on a single radio cell served by a single base station. The simulation addresses the inbound channel only (terminals to base), and it is assumed that any control or acknowledgment signal is transmitted on the outbound channel, and is received without delay or error.

The number of terminals within the radio cell is limited, but terminals are capable of generating various types of real-time (RTT), and non-real-time (NRTT) traffic at different bit rates. Figure 4.2 shows a conceptual schematic of the system. The time is assumed to be slotted, where each slot can accommodate an ATM standard cell (53 bytes). There are two separate queues, one for RTT and the other for NRTT. The generated information is packetized into ATM cells, time stamped and placed in one of the two queues. The RTT has priority over NRTT, meaning that the terminals try to empty the RTT buffer first. The terminals as well as the controller (base) are assumed to be synchronized. The network is assumed to be in steady state with no new connection establishment or connection termination. A selective repeat ARQ is employed to recover the erroneous received cells from both traffic types.

4.5.2 Traffic Model

The ARMA model, proposed in [25], is used to generate the RTT. The model is shown in figure 4.3. $\{\epsilon_i\}$ is a white noise sequence fulfilling $\bar{\epsilon}_i = 0$. The τ 's are delay elements corresponding to the duration of 64 ATM cells size slots. The order of the transversal filter ($2q$) is determined based on the time distance between correlation peaks of typical coded video sequence. The ZNML is a zero memory nonlinear filter defined as: $X_i = \text{Max}(0, \sqrt{\text{Var}(X)} \cdot V_i + \bar{X})$. $\{v_i\}$ is a zero mean white Gaussian noise whose variance is determined using samples of measured autocovariance function of coded video

Figure 4.2 The schematic diagram of the system

Figure 4.3 The block diagram of ARMA model for VBR video traffic

sequence. The output of the system models the coded video at the block of 64 time slots level.

The generated cells must be delivered within their maximum transfer delay (MTD), and are discarded if they are delayed longer than the MTD. The performance criterion of the RTT is the cell loss probability. The NRTT is assumed to be bursty, and is modeled by ON-OFF Markov process. The ON and OFF states both have exponential distributions with 34 msec mean, meaning that the peak bit rate is twice the mean bit rate. The NRTT, is assumed to be able to tolerate long delay, so NRTT cells are not discarded. The performance criterion for the NRTT is the average cell delay. The aggregate traffic is a mix of RTT consisting of 20 Mbps HDTV, 1.5 Mbps MPEG video, 64 kbps compressed video conferencing, and NRTT consisting of 12.6 Mbps and 10 kbps data transfers, and 2 Mbps still image. This traffic is assumed to be transported over a 155.5 Mbps link. The details of the simulation scenarios can be found in [68].

4.5.3 Channel Model

The radio channel is assumed to alternate between the good state (ON), and the bad state (OFF). The duration of the ON-state is an exponential random variable, and the duration of the OFF-state is assumed to be constant and equal to 10 ATM cell size slots. The second assumption is reasonable under the condition that as soon as the base station senses the channel failure, instructs the communicating remote to invoke a corrective action (with a certain latency).

4.5.4 Multiple Access Scheme

The service discipline is G-limited polling. The limits on the service times are determined using the declared mean bit-rates. The number of slots allocated to user j with mean cell rate $\bar{\mu}_j$, in the i^{th} cycle is:

$$W_j = \text{Min}(QL_{i,j}, k_j) \quad (4.11)$$

where the function $\text{Min}(\dots)$ takes the minimum value of its two arguments, $QL_{i,j}$ is the user's queue length at the polling instant and k_j is the service limit, and is equal to:

$$k_j = \left\lfloor \frac{\bar{\mu}_j}{\sum_{i=1}^N \bar{\mu}_i} \cdot C_L \right\rfloor \quad (4.12)$$

where $\lfloor . \rfloor$ returns the integer part of its argument, N is the number of the connected remotes, and C_L is the cycle time limit. The polling overhead is assumed to be two ATM cells per user.

4.5.5 Simulation Results

The system has been examined under the 88%, 83%, 78%, and 73% net utilizations (without considering ATM cell overhead). The simulation runs have been 10^6 ATM cells long. The effects of Cycle time limit, channel failure, and utilization on the measured performance are presented in the next sections.

Cycle Time Effects:

Figure 4.4 illustrates the loss probability of RTT and the average delay of NRTT for 88% utilization with four cycle time values (2000, 4000, 8000, 16000 ATM cells). As we discussed before there is an optimum value for the cycle time limit. The least loss rate is achieved at $C_L=4000$ ATM cells which is equal to 9.96 msec. For C_L less than 9.96 msec the polling overhead is noticeable. A C_L larger than 9.96 msec imposes high delay on RTT, therefore the dropping probability rises. The average delay for NRTT is monotonically decreasing for the cycle limit varying in the range of 2000 to 16000 ATM cells.

Effects of the Channel Failure:

Figure 4.5 represents the effect of the channel failure on the loss probability of RTT and the average delay of NRTT at 88% and 83% utilizations. As expected, higher channel failure results in higher loss and delay. Since we assumed ARQ, the channel failure can be compensated, when the utilization is low.

Figure 4.4 The loss rate for RTT and the average delay for NRTT with 88% utilization and channel failure 1%, under four cycle time limits

Figure 4.5 The RTT loss rate and the NRTT average delay vs. channel failure for 88% and 83% utilizations, and cycle time limits are 4000 ATM cells and 6000 ATM cells respectively.

Utilization Effects:

It can be noticed from figure 4.6 that, as the utilization decreases the loss probability below 10^{-5} is achievable at lower MTD and the average delays have a lower asymptotic values. The best loss and delay profiles for utilizations 88%, 83%, 78%, and 73% are achieved at C_{max} equal to 4000, 6000, 8000, and 10000 ATM cells respectively. For low utilization, the best performance is obtained under 10000 ATM cells cycle time limit. This is because at a low utilization, while many of the queues contain less cells than their limits, the service limits doesn't allow the long queues to empty their bursts. Therefore, when the cycle time is short, the bursts remain in the system, causing cell drops and excessive delay. As the result, the system works better under larger cycle limit. However when the utilization is as high as 88% the best performance is achieved at $C_L=4000$ cells. This is because a short cycle time prohibits strong bursts to block the link during the burst period.

4.6 Improving the Performance of FGL Polling

4.6.1 The Non-Uniform Polling Technique

As equation (4.10) implies, for a certain cycle limit, reducing the polling overhead, increases the utilization. We mentioned in the section 4.4.3 that the limit on the cycle time may be imposed by the most delay sensitive applications. Being so, the polling cycle would be too short for the slow, tolerant to long delay sources. In a regular polling scheme, such a user is polled in every cycle, while there is no cell in its buffer most of the times. In the other words, part of each cycle is wasted for polling empty queues.

In the *non-uniform polling*, the basic idea is to poll each remote as frequently as its traffic parameters and requirements necessitate. For each type of traffic a certain cycle limit would be obtained. The smallest cycle limit is called the "basic polling cycle" (BPC). Other cycle limits are multiples of the BPC, so not all the connected remotes are polled in every BPC. Low data rate sources have larger polling cycles, i.e. they are polled less frequently. In this way the polling overhead will be reduced, especially when we have considerable number of low bit rate sources, and a few number of high bit rate sources in the system.

Figure 4.6 The cell loss probability for RTT and the average delay for NRTT under the 88%, 83%, 78%, and 73% utilizations with proper cycle time limits, and channel failure rate 1%

From another point of view, the non-uniform polling, can be considered as the class related multiplexing, described in section 4.2.1. In every BPC, a certain number of slots belongs to a class of less-stringent sources. But only one of the members of the class is polled and served in each BPC.

4.6.2 Comparing the Performance of the Uniform and the Non-uniform Polling

In the non-uniform polling, the polling cycle is not the same for different users. In this section, the polling frequency for each user is determined only based on its mean bit rate. For instance, while a 20 Mbps source is served in each cycle, the 1.5 Mbps source is served every $[20/1.5] = 13$ cycles. In return, all the users polled in a cycle receive equal amount of service. The simulations results are shown in figures 4.7 and 4.8. The non-uniform polling presents somewhat better fairness. For this method the overall loss probability goes below 10^{-5} for MTD equal to 49 msec which is less than the corresponding one for the uniform polling. The mean delay of the NRTT has increased by applying the non-uniform polling. This is due to the lower priority of the NRTT.

In these simulations, for both of the uniform and the non-uniform polling, only the mean bit rates of the sources are used in slot assignment procedures. The important conclusion from figure 4.6 is that, bandwidth allocation based on mean bit rates is unfair toward more delay sensitive traffic. The 20 Mbps sources which have higher level of burstiness and smaller MTD, suffer from much more cell loss rate than 1.5 Mbps sources. As stated in section 4.2.2, to obtain fairness, some traffic parameters reflecting the burstiness, and the required QOS have to be taken into account.

4.7 Conclusion

In this chapter, first, the bandwidth management methods in fast ATM networks were reviewed briefly. It was pointed out that the basic objectives in such a system are optimum utilization of available bandwidth, fairness toward all supported traffic types, and satisfying the users' QOS. In continue, the limited polling based multiple access methods were considered. Presenting the mean cycle time analysis, we showed that for a given mix of traffic, there is an optimum cycle time limit under which the system reaches its best performance. Then the effects of CFR, MTD, and cycle length on the FGL polling

Figure 4.7 The loss rates of two real-time applications for the uniform polling and the non-uniform polling. Utilization, cycle time limit and channel failure are 88%, 4000 and 1% respectively.

Figure 4.8 The cell loss rate of RTT and the average delay of NRTT for the uniform and the non-uniform polling. Utilization is 88%, cycle time limit is 4000 ATM cells and channel failure rate is 1%.

performance were studied by simulations. To improve the FGL polling performance, the non-uniform polling technique was presented and simulated. It was shown that although the non-uniform polling improves the system performance, nevertheless if its parameters are chosen regardless of the radio link condition and the required QOS, the improvement won't be substantial.

In the next chapter we will present the analysis of a symmetric FGL polling system leading to an upper limit on the utilization which guarantees the connection quality. This limit will be used later to obtain the proper values for the non-uniform polling parameters.

Chapter 5

The Upper Bound on Channel Utilization in Cyclic Service Discipline with Bursty Arrivals

5.1 Introduction

In the previous chapter, we noticed that, if the non-uniform polling parameters are determined exclusively based on the mean bit-rates, the system suffers from unfairness problem and the performance improvement will not be substantial.

Consider the non-uniform polling explained in the previous chapter. Two parameters have to be determined for each active user j : the inter visit interval (polling cycle, (C_j) , and the maximum number of the slots provided to the user in each visit (k_j). To have an efficient bandwidth allocation, the following factors should be taken into account for determining the C_j and the k_j :

- (1) the radio channel failure rate,
- (2) the traffic statistical characteristics which indicate the burstiness of the source as well as its average data rate,
- (3) the QOS requirements of the source which mainly are the MTD and target loss probability

To obtain a basis for considering the above mentioned factors in designing the non-uniform polling, in this chapter, an upper limit is derived for the utilization which guarantees the service quality in a symmetric FGL polling system. Later on, based on the maximum utilization, a procedure is presented which produces the proper parameters for the non-uniform polling method.

5.2 The Upper Band on Utilization in a Symmetric FGL Polling System

5.2.1 Analytical Model

In this analysis the cyclic service system is considered to be symmetric namely:

- (1) All sources are statistically identical. Each source is modeled by the sum of M i.i.d. *ON/OFF* mini-sources, each one producing cells in the *ON* state at a rate of γ cells/slot. Assuming that each mini-source is in the *ON* state with probability π_{ON} , then, the mean cell arrival rate per user is $\bar{\mu} = \pi_{ON} \cdot \gamma \cdot M$.
- (2) All remotes are connected to the base station by statistically identical radio channels. The average channel failure rate is '*CFR*', and the status of the channels are independent from each other and from cycle to cycle.
- (3) The size of the overhead in each access cycle is assumed to be fixed and identical for all the active users.

In this analysis the radio cell is considered to be in isolation, so the *CFR* is independent from utilization. The system is working in steady state with no new connection establishment or connection termination. The system is assumed to operate near saturation.

5.2.2 The Mean and The Variance of Queue Length at The Polling Instant

Consider the system described in previous section, where the N sources are identical. The number of cells generated by a single user in cycle ' i ' is a binomial random variable with an average value of $(\bar{\mu} \cdot C_i)$, and the total number of cells generated by all users in the cycle is a random variable having the N -fold convolution of statistically identical and independent binomial variables and has an average value of $N \cdot (\bar{\mu} \cdot C_i)$. We define the channel utilization, ρ , as the ratio between the average number of new cells generated in a cycle and the cycle length in time slots; i.e.

$$\rho = \frac{N \cdot \bar{\mu} \cdot C_i}{C_i} = N \cdot \bar{\mu} \quad (5.1)$$

ρ can be further described as the probability of having a new cell in a time slot from any of the connected sources. Also, we can write:

$$C_L = K + S \quad \text{and} \quad \bar{C} = N \cdot \bar{W} + S \quad (5.2)$$

where

$$K = N \cdot k \quad \text{and} \quad S = N \cdot s \quad (5.3)$$

where C_L is the cycle time limit, k is the service time limit for each queue and K is the total service time in a cycle. N is the number of queues, and s is the overhead for each user and S is the total overhead in a cycle, and $\bar{W}$ is the mean service provided to each user which is given by:

$$\bar{W} = \frac{\bar{\mu} \cdot \bar{C}}{1 - CFR} = \bar{\mu} \cdot \frac{N \cdot s}{1 - \rho - CFR} \quad (5.4)$$

Consider a symmetric FGL polling system in which the queues may violate their quotas as long as the cycle time limit is preserved. Such a system, behaves like a single queue system. Suppose that the channel utilization satisfies the following inequality:

$$0 < (1 - CFR) (C_L - S) - \rho C_L < 1 \quad (5.5)$$

The above inequality intuitively means that to maintain stability the network resources should be more than the total offered traffic load. In Appendix B.1. we show that when the condition given in (5.5) is satisfied, the mean queue length at the arrival of the server to each queue is equal to:

$$\bar{V}_{HL} \approx \frac{\frac{\sigma_\mu^2}{\bar{\mu}} \rho}{2 \left((1 - CFR) \rho_o - \rho \right)} \quad (5.6)$$

where σ_μ^2 is the variance of the cell generation rate per user and ρ_o is equal to:

$$\rho_o = \frac{(C_L - S)}{C_L} \quad (5.7)$$

By similar technique, the following approximation for the variance of the queue length at the visiting instant, under heavy load and high utilization, is obtained in appendix B.2:

$$\sigma_{V_{HL}}^2 \approx \frac{\left(\frac{\sigma_\mu^2}{\bar{\mu}}\right)^2 \rho^2}{4((1 - CFR)\rho - \rho)^2} \quad (5.8)$$

To investigate how good are the above approximations, the mean and the variance of the queue length at the visiting instant, in a symmetric non-uniform polling system with 10 identical 1 Mbps mean bit rate sources, each one modeled by 10 ON-OFF mini-sources with burstiness 4, is simulated. The results of simulations, illustrated in figures 5.1 to 5.8, show that in the vicinity of saturation, equations (5.6) and (5.8) present good estimates for $\bar{V}_{HL}$ and $\sigma_{V_{HL}}^2$.

5.2.3 The Upper Bound on Channel Utilization

For a non-negative random variable X , with mean $\bar{X}$ and variance σ_X^2 , for any $a \geq \bar{X}$ one can write the Markovian inequality as:

$$p(X \geq a) \leq \frac{1}{1 + \frac{(a - \bar{X})^2}{\sigma_X^2}} \quad (5.9)$$

Using the above inequality and having (5.6) and (5.8), the upper bound for the overflow probability can be derived as:

$$p(V \geq B_{max}) \leq \frac{1}{1 + \frac{(B_{max} - \bar{V})^2}{\sigma_V^2}} \quad (5.10)$$

where B_{max} is the buffer limit. The above upper bound is rather loose. One may think of approximating the overflow probability by exponential or normal distribution. To find the best choice of these three, the system is simulated with the offered load equal to the aggregate traffic generated by one hundred mini-sources each one with 0.21 Mbps mean bit rate, activity ratio 0.25, and average ON period 33 msec. The probability of overflow

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PM-1 3½" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

Figure 5.1 The mean queue length at the visiting instant vs. utilization. The simulation results and the analytical values given by Eq. (5.6) and Eq. (B.13) from appendix B, cycle limit=500 cells, channel failure rate=10%

Figure 5.2 The mean queue length at the visiting instant vs. utilization. The simulation results and the analytical values given by Eq. (5.6) and Eq. (B.13) from appendix B, cycle limit=500 cells, channel failure rate=5%

Figure 5.3 The mean queue length at the visiting instant vs. utilization. The simulation results and the analytical values given by Eq. (5.6) and Eq. (B.13) from appendix B, cycle limit=500 cells, channel failure rate=0%

Figure 5.4 The mean queue length at the visiting instant vs. utilization. The simulation results and the analytical values given by Eq. (5.6) and Eq. (B.13) from appendix B, cycle limit=200 cells, channel failure rate=5%

Figure 5.5 The variance of the queue length at the visiting instant vs. utilization. The simulations and the analytical results given by equations (5.8) and (B.18). cycle limit=500 cells, channel failure rate=10%

Figure 5.6 The variance of the queue length at the visiting instant vs. utilization. The simulations and the analytical results given by equations (5.8) and (B.18). cycle limit=500 cells, channel failure rate=5%

Figure 5.7 The variance of the queue length at the visiting instant vs. utilization. The simulations and the analytical results given by equations (5.8) and (B.18). cycle limit=500 cells, channel failure rate=0%

Figure 5.8 The variance of the queue length at the visiting instant vs. utilization. The simulations and the analytical results given by equations (5.8) and (B.18). cycle limit=500 cells, channel failure rate=5%

versus the buffer length, along with the complement of the cumulative distribution function (cdf) of exponential and normal distributions, and the Markov bound are illustrated in figures 5.9 to 5.14. The results show that near saturation the overflow probability can be well approximated by the complement of the exponential cumulative distribution function. Therefore, an approximate equation can be derived as:

$$Prob(V \geq B_{max}) \approx Exp(-\frac{B_{max}}{\bar{V}}) \quad (5.11)$$

To obtain the upper bound on utilization based on QOS requirements we substitute the cell loss probability by the overflow probability and the MTD by the queue length in Eq. (5.11). Doing so, the following inequality can be derived:

$$\frac{MTD - \bar{V}}{\sigma_V} \geq f(P_{loss}) \quad (5.12)$$

where P_{loss} is the target cell loss probability, and $f(P_{loss})$, depending on whether Markov bound or exponential approximation is used, is equal to:

$$\text{Markov bound} \Rightarrow f(P_{loss}) \approx \frac{1}{\sqrt{P_{loss}}} \quad (5.13)$$

$$\text{Exponential approximation} \Rightarrow f(P_{loss}) = -\ln(P_{loss}) \quad (5.14)$$

Substituting (5.6) and (5.8) into (5.12) results in a bound for the utilization:

$$\rho_G \leq G \cdot (1 - CFR) \cdot \rho_s \quad (5.15)$$

where ρ_G is the utilization under which the cell loss and delay requirements of the connected sources are guaranteed, and

$$G = \frac{2MTD}{2 \cdot MTD - \ln(P_{loss}) \cdot \frac{\sigma_\mu^2}{\bar{\mu}}} \quad (5.16)$$

Figure 5.9 Comparing the overflow probability, the Markov limit, and (1-cdf) of exponential, and Gaussian distributions. Channel failure rate 0%, utilization 90.0%, the system works rather far from saturation.

Figure 5.10 Comparing the overflow probability, the Markov limit, and (1-cdf) of exponential and Gaussian distributions. Channel failure rate 0%, utilization 97.2%, the system works close to saturation.

Figure 5.11 Comparing the overflow probability, the Markov limit, and (1-cdf) of exponential, and Gaussian distributions. Channel failure rate 5%, utilization 89.4%, the system works rather far from saturation.

Figure 5.11 Comparing the overflow probability, the Markov limit, and (1-cdf) of exponential, and Gaussian distributions. Channel failure rate 5%, utilization 89.4%, the system works rather far from saturation.

Figure 5.12 Comparing the overflow probability, the Markov limit, and (1-cdf) of exponential, and Gaussian distributions. Channel failure rate 5%, utilization 91.7%, the system works close to saturation.

Figure 5.13 Comparing the overflow probability, the Markov limit, and (1-cdf) of exponential, and Gaussian distributions. Channel failure rate 10%, utilization 84.6%, the system works rather far from saturation.

Figure 5.14 Comparing the overflow probability, the Markov limit, and (1-cdf) of exponential, and Gaussian distributions. Channel failure rate 10%, utilization 86.8%, the system works close to saturation.

The inequality (5.15) nicely relates the network parameters to the user characteristics, and shows the effect of each parameter on the maximum utilization. The term $(1 - CFR)$ indicates the effect of channel failures, and the term ρ_0 shows how the overhead limits the best achievable utilization. Finally the term G given in equation (5.16) illustrates the effects of traffic requirements and traffic burstiness on the maximum utilization.

The bound in (5.15) applies to various situations. For instance, if the MTD for a bursty application is too large, $G \approx 1$, the traffic can be smoothed out by buffering the bursts, such that the utilization can be as high as $(1 - CFR)$. When the delay requirement is stringent, the “burstiness” of the source and the “target cell loss probability” play important roles in reducing the maximum achievable utilization. For a source with small target cell loss probability, if the burstiness is zero the utilization can reach $(1 - CFR)$. However, to fulfill the requirements of a bursty source with P_{loss} close to zero ($G \ll 1$), the utilization should be very small.

To show that substituting the cell loss probability by overflow probability and the MTD by the buffer length results in a true upper bound on the channel utilization in the vicinity of saturation, the system has been simulated. In these simulations the offered load is the aggregate traffic generated by one hundred mini sources each one with 0.22 Mbps mean bit rate, activity ratio 0.25, and average ON period 33 msec. The cycle limit is equal to 200 cells with 10 cells overhead in each cycle. Figures 5.15 and 5.17 show that the overflow probability is higher than the cell loss probability at high utilization levels.

5.3 Conclusion

In this chapter, we obtained approximate expressions for the mean and the variance of the queue length at the polling instant, in a symmetric cyclic system, under heavy traffic load condition. Using these approximations, the upper bound on the utilization which guarantees the user QOS requirements was derived. In the next chapter we utilize the maximum utilization to obtain the proper design for nonuniform slot allocation procedure under mixed traffic conditions.

Figure 5.15 Evaluating loss Probability and MTD estimations by overflow probability and buffer length. The channel failure rate is 1%.

Figure 5.16 Evaluating loss Probability and MTD estimations by overflow probability and buffer length. The channel failure rate is 4%.

Figure 5.17 Evaluating loss Probability and MTD estimations by overflow probability and buffer length. The channel failure rate is 10%.

Chapter 6

Non-uniform Polling and Non-uniform Slot Reservation Protocols

6.1 Introduction

In this chapter we propose a bandwidth allocation procedure, based on the non-uniform polling method using the upper bound on utilization which was derived in the last chapter. It is important to notice that the following discussions, as it is clear from the notion of the arguments, are about bandwidth management for bursty traffic. Accommodating CBR or well behaving traffic is a trivial task which is not the subject of this study.

The parameters which will be considered in bandwidth allocation consist of the mean cell arrival rate, the variance of the arrivals, the MTD, the target loss probability, and the number of cells present in the user buffer. The first four parameters are the ones which the user declares at the call setup, and every time wants to change its type of connection. These parameters are called "*the static parameters*". The last parameter is to be collected in every visit of the server to each user. The static parameters are utilized to determine those factors in the bandwidth allocation procedure which remain unchanged as long as the network is in a particular steady state situation. The buffer length information is put to use to consider the transient property of the heterogeneous traffic in the bandwidth allocation procedure.

6.2 The Non-uniform Polling Slot Assignment Procedure

6.2.1 The Service Assignment Parameters

Based on the equations we derived in the previous chapter, the two parameters in non-uniform polling are obtained as below:

- 1- Substituting the maximum utilization from inequality (5.15) into (5.5), and using Eq. (5.7) we obtain the following inequality which involves the cycle limit C_L as:

$$0 < (1 - CFR) (C_L - S) - G (1 - CFR) (C_L - S) < 1 \quad (6.1)$$

$$C_L < S + \frac{1}{(1 - G) (1 - CFR)} \quad (6.2)$$

One can satisfy inequality (6.2) by choosing C_L as:

$$C_L = \frac{1}{(1 - G) (1 - CFR)} \quad (6.3)$$

where

$$G = \frac{2MTD}{2 \cdot MTD - \ln(P_{loss}) \cdot \frac{\sigma_\mu^2}{\bar{\mu}}} \quad (6.4)$$

Based on equation (6.3), if the MTD goes to infinity, the cycle limit can be very large. In the other extreme, suppose that the channel is perfect and MTD approaches zero. In this case the cycle limit can be no more than one cell and that is the limited-1 or non-exhaustive polling service discipline.

- 2- Using (5.1) to (5.3) and (5.15), the service limit during each cycle is calculated as:

$$k = \frac{\bar{\mu} \cdot C_L}{G (1 - CFR)} \quad (6.5)$$

As an example, for a 1.5 Mbps source with variance to mean ratio equal to 0.98, 10^{-4} loss probability, 50 msec MTD , 155 Mbps link capacity, and $CFR = 0.05$, the cycle time limit

is 4264 slots which is 11.66 msec. The service limit for each user would be 44 slot, so if the overhead per user is two cells, the system can accommodate up to 92 users.

6.2.2 Slot Assignment in General Situations

Under mixed traffic condition, each user has a different set of parameters, and the whole system consists of N queues, each one with its own characteristics. When the traffic load is light, the behavior of the N queues will be strongly inter-dependent because the base station assigns any un-used slot to users with long queues. Under heavy traffic conditions, however, each user requires its guaranteed minimum bandwidth, so the queues interactions are minimum and the N queues most likely act independently from each other. Therefore regardless of how the rest of the network is operating, for a user ' j ' with the four static parameters: $\bar{\mu}_j$, σ_j^2 , MTD_j , and $(p_{loss})_j$, if k_j number of slots, given by Eq. (6.3) is assigned to user j in a cycle time of $(C_L)_j$, given by Eq. (6.5), its traffic requirements will be fulfilled.

The above bandwidth is obtain for heavy load situation, however if the total offered load is low, the connected users may enjoy less tight restriction than the above limits. Shall the static parameters of a source change (e.g. requesting additional service, or changing the service requirements), the controller has to go through the above procedure again to allocate proper quota to the user.

6.2.3 Admission Control Procedure

The ratio k_j/C_j is the fraction of the available bandwidth which is allocated to user j to satisfy its QOS requirements. This ratio can be interpreted as "*the virtual bandwidth*" for a connection of class j , normalized to the link capacity. The normalized virtual bandwidth for the user ' j ' is equal to:

$$VBW_j = \frac{\bar{\mu}_j}{G_j \cdot (1 - CFR)} \quad (6.6)$$

The above equation allocates to each user a bandwidth equal to the mean bit rate multiplied by $\frac{1}{G(1 - CFR)}$, which accounts for the effects of traffic properties and channel failure rate.

Thus, as the call admission policy, a requested connection of class j can be admitted to the network, if the above bandwidth is affordable.

6.3 Non-Uniform Polling Multiple Access Protocols

6.3.1 Bandwidth Allocation Procedure

Consider a radio cell where N users are connected to a single base station and share a common radio channel. The service allocation in non-uniform polling method is described as follows:

- (1) A Basic Polling Cycle (BPC) is determined based on the system properties regarding the most stringent QOS requirements of the supported traffic types, or radio transmission conditions.
- (2) Each user declares its traffic parameters (traffic statistical characteristics and traffic requirements) during the call setup procedure. The user may request to change its type of connection during the call, but the base station controller must know the traffic parameters of each user at all times.
- (3) The controller assigns a polling frequency for each user, $(C_L)_j = q_j \times BPC$; $j=1, 2, \dots, N$, where, $1 < q_j < q_{max}$. This means that the k^{th} user is to be polled every $q_k BPC$. High data rate users with stringent delay requirements are polled more frequently (e.g. every BPC).
- (4) At the start of each BPC , the controller polls the users scheduled for transmission in that cycle, and allocates time slots according to the following procedures:

Let: m = the number of users to be visited in the BPC

T_j = the service time requested by user # j in the BPC ; $j = 1, 2, \dots, m$.

G_j = the service time allocated to user # j in the BPC ; $j = 1, 2, \dots, m$

k_j = maximum service time for user ' j ' under heavy load condition

Then the number of allocated time slots would be:

- I) If $T_j > k_j$ for $j = 1, 2, \dots, m$ then: $G_j = k_j$
- II) If $T_j \leq k_j$ OR $\sum_{j=1}^m T_j < BPC$ then: $G_j = T_j$
- III) In the case that some of the remotes have more cells to transmit than their limits and some of them have less, the following approach can be used:

Assuming that T_j is in ascending order so that: $T_1 \leq T_2 \leq \dots \leq T_m$;

If $T_i \leq k_i$ for $i = 1, \dots, l$ ($1 \leq l \leq m$) and $T_j > k_j$ for $j = l+1, \dots, m$, then:

$$\left\{ \begin{array}{l} G_i = T_i \text{ for } i = 1, \dots, l \text{ and} \\ G_j = \min\left(T_j, k_j + \left(\sum_{n=1}^l (k_n - T_n)\right) \cdot \left(k_j / \sum_{n=l+1}^m k_n\right)\right) \text{ for } l < j \leq m \end{array} \right\}$$

this procedure is repeated until $\sum_{j=1}^m G_j = BPC$

If it so happens that the allocated time G_j is less than the requested time, T_j , the j^{th} user will have some leftover data that will be delayed for q_j polling cycles.

(5) When polled, the j^{th} user transmit G_j cells. All cells that encounter channel failure are re-scheduled for transmission in the next polling cycle and are placed at the top of the j^{th} user queue; i.e., Automatic Repeat reQuest (ARQ) is applied to all cells, and cells are discarded only when their MTD expires.

The scheme described above has the following advantages:

- (1) The scheme avoids frequent communications with terminals that are known to be slow. This saves on the polling overhead associated with such communications. A secondary advantage is that those slow terminals can save power by avoiding unnecessary exchanges with the base.
- (2) The scheme takes advantage of the traffic statistical variations of polled users by allowing users with $T_j > k_j$ to continue transmitting beyond their assigned limits when some other users don't need their maximum service times.

These two advantages are amplified when few VBR video terminals share the radio link with many low data terminals, a scenario that is likely to prevail in wireless local area networks.

6.3.2 Detailed Description of The Protocol

In figure 6.1 the structure of a basic polling cycle is shown. Each *BPC* contains two sections: (1) a short period which is called the control section and (2) another section which contains the data cells and is called the data section. The first few slots in the control section are used for radio signaling, channel maintenance, pilot and beacon signals, etc. This is followed by a short period allocated for random access by new users in every several *BPC*, depending on access delay requirement. This period is marked by a special pilot signal. Receiving the pilot a new user sends the connection request to the base station. The request includes the following information: (1) the mean and the variance of the user cell rate, (2) its *MTD* and target cell loss probability, and (3) the number of cells in its buffer. Upon receiving the connection request, the controller calculates the user virtual bandwidth using equation (6.6) and determines whether the requested connection can be supported by available bandwidth. If the connection is affordable, the controller accepts the request and then determines the visiting period and the service limit of the new user and starts to poll it accordingly.

The data section has three parts. The first part contains the down-stream traffic, during which the base station forwards the incoming traffic to remotes within the radio cell. Following the down-stream part, the base station starts to poll those remotes which should be served during the *BPC*. Each polled remote has to specify the number of slots it needs to empty its buffer during the service time. Finishing the polling, the base broadcasts a schedule table containing the name, the order of service and the number of allocated slots to the remotes which are going to be served during the data section. Each remote which finds its name in the schedule table occupies the slots in the up-stream part (remotes to base) which are allocated to it according to the order and number of cells specified in the table. At the end of service time, each remote acknowledges the base station that it has received the down-stream cells and requests the repeat if any cell is missing or erroneous. The radio link agreements (such as switching to another pair of antennas in antenna diversity) can be performed in this period as well. After the up-stream part, the controller broadcasts the acknowledgment of the cells received from the remotes and requests the repeat if any cell is missing or erroneous.

Figure 6.1 The structure of a Basic Polling Cycle (BPC)

Figure 6.1 The structure of a Basic Polling Cycle (BPC)

In the next section, we verify the performance of the non-uniform polling method by a simulation study.

6.4 Non-Uniform Polling Simulations

6.4.1 Simulation 1

To examine the performance of the non-uniform polling, the following simulation has been performed. The simulation addresses the inbound channel only (terminals to base). So the utilization can be defined as the total load offered by all connected sources divided by the bandwidth which is allocated to the up-stream traffic. Three types of source were assumed:

- 1- Two 4.42 Mbps sources including ATM cell overhead (e.g. MPEG VBR video), with the burstiness (peak bit-rate to mean bit-rate ratio) equals to 4, $MTD=40$ msec and $P_{loss} = 10^{-4}$. Each of these two sources is modeled by a set of 20 Markovian ON-OFF mini-sources with 0.25 activity ratio (the percentage of the time that the mini-source is ON), and 33 msec mean ON duration.
- 2- Eight 352 kbps sources (e.g. video conferencing) with burstiness 3, $MTD=150$ msec and $P_{loss} = 10^{-4}$. Each of the sources is modeled by 15 ON-OFF mini-sources, with 0.32 activity ratio, and 33 msec mean ON duration.
- 3- Ten 1.1 Mbps sources (e.g. data or still image transfer) with burstiness 20, $MTD=1$ sec and $P_{loss} = 10^{-6}$, each one modeled by one ON-OFF source with 0.05 activity ratio, and 0.1 second ON duration.

The fade duration is modeled by exponential distribution with 10 ATM cells mean, interrupted when the service time is over. The exponential pdf is assumed for the non-fade duration as well. The polling overhead is assumed to be 2 ATM cells per user, in each polling cycle. The time unit has been an ATM cell, and the simulation is performed for 2×10^6 ATM cells. The terminals as well as the controller (base) are assumed to be synchronized. The network is assumed to be in steady state with no new connection establishment or connection termination. A selective repeat ARQ is assumed to be

employed to recover the erroneous received cells from all traffic types. In these simulation the Markov bound is used to obtain the non-uniform polling parameters.

Figures 6.2 and 6.3 show the mean cell loss rate for the first two types of traffic in gated (non-limited) polling system, FGL polling system, and non-uniform polling system. The cell loss rate for the third type of traffic has been below 10^{-6} in all the three polling schemes.

The cycle limit for the FGL polling scheme was set to 1500 slots and the limit on the service time is determined using the mean bit-rates, as explained below. The number of slots allocated to user j with mean bit rate $\bar{\mu}_j$, in the i^{th} cycle is:

$$W_j = \text{Min}(QL_{i,j}, k_j) \quad (6.7)$$

where the function $\text{Min}(. , .)$ takes the minimum value of its two arguments, $QL_{i,j}$ is the user's queue length at the polling instance and k_j is the service limit which is given by:

$$k_j = \left\lfloor \frac{\bar{\mu}_j}{\sum_{i=1}^N \bar{\mu}_i} \cdot C_L \right\rfloor \quad (6.8)$$

where $\lfloor . \rfloor$ returns the integer part of its argument, N is the number of the connected remotes, and C_L is the cycle time limit.

This study confirms that the non-limited polling presents a poor performance for bursty traffic, when the delay constraint is stringent. The improvements achieved by FGL polling and the non-uniform FGL polling with the proposed method are noticeable.

The buffer occupancy for the three traffic types is monitored as an indication of imposed delay, and illustrated in figures 6.4 and 6.6, for the gated and the non-uniform polling. The cell loss rate for non-uniform polling is much less than gated polling, so there are more cells in the non-uniform polling system, and consequently the buffer occupancy is generally higher. Although the 1 Mbps sources have less stringent delay requirements (1

Figure 6.2 Mean cell loss rate for the three polling methods vs. channel utilization for CFR=0.05. Solid lines are related to 4Mbps sources, and dotted lines are related to 0.32 Mbps sources.

Figure 6.3 Mean cell loss rate for the three polling methods vs. channel utilization for CFR=0.01. Solid lines are related to 4Mbps sources, and dotted lines are related to 0.32 Mbps sources.

Figure 6.4 Mean buffer occupancy for ordinary and non-uniform polling vs. channel utilization. The channel failure rate is 5%.

Figure 6.5 Mean buffer occupancy for ordinary and non-uniform polling vs. channel utilization. The channel failure rate is 1%.

second), in gated (non-limited) polling, they block the link by their strong bursts. So the delay imposed on 1 Mbps sources is less than the delay imposed on 4 Mbps sources in the gated polling system. While in the non-uniform polling system the strong bursts are dumped by properly buffering them. Therefore, higher delay is imposed on 1 Mbps sources to provide better performance for 4 Mbps sources.

6.4.2 Simulation 2

In this section we present the results of another set of simulations which compare the performance of non-uniform polling and a modified polling method proposed in [117]. In this modified polling method, the base regularly polls each remote. When polled, the remote either transmits a request or transmits a short response indicating that there is no request to send. A remote having a waiting request is defined to be a *non-empty remote*. After the base has polled each of the remotes, it begins to respond to the non-empty remotes. The service discipline which defines the order of response to non-empty remotes can be FIFO, shortest request-response time first, or priority based, etc. A time clock is set to zero at the start of each polling period. Each polling period begins either when the base has finished responding to all non-empty remotes or when the clock reaches some time out value T , whichever occurs first, where T is set by the rate-of-change of the environment. If the base has finished responding to non-empty remotes before the time clock reaches T , a new polling cycle begins. If the base has not finished responding to those non-empty remotes when the time clock reaches T , the base stops responding and again polls each remote; after polling, the base resumes its response to the remotes, starting from where it left in the previous cycle [117]. The performance of this method with FIFO service discipline has been evaluated for a rather smooth type of traffic modeled by Poisson process without severe delay constraint. For a polling cycle of 20 msec and a network containing 10 or 50 users, the maximum link efficiency had been 97% and 87% respectively, assuming that the link speed is 5 Mbps [117].

The above modified polling scheme can be categorized in non-limited polling schemes, since the base station serves each remote until the work is finished. The purpose of this comparison is to show that for a multiple access scheme which is designed for smooth traffic, the heterogeneous multimedia traffic is a break point. However, the non-uniform polling performs well in such a situation.

The simulations address the up-stream traffic only. So again, the utilization is defined as the total load offered by all connected sources divided by the bandwidth which is allocated to up-stream traffic. The network is assumed to be in steady state, meaning that there is no new connection establishment or termination during the simulation. The ON period of the radio channel is assumed to have an exponential distribution. However in this simulation, the OFF period is only interrupted by the end of service time.

The source configuration is as follows:

- 1- Four 1.5 Mbps sources (1.66 Mbps including ATM cell overhead), with $MTD = 40$ msec. and target loss probability equal to $P_{loss} = 10^{-4}$. Each source is modeled by 20 Markov mini-sources, each one with 0.3 activity ratio (the percentage of the time that the mini-source is ON), and 33 msec mean ON duration (e.g. MPEG video).
- 2- Twelve 0.64 Mbps sources (0.707 Mbps including ATM cell overhead), with $MTD = 1$ sec and target loss probability equal to $P_{loss} = 10^{-6}$. Each source is modeled by one Markov ON-OFF source with 0.1 activity ratio (burstiness 10), and 100 msec mean ON duration (e.g. data transfer).

In these simulations the BPC is assumed to be 10 msec. The overhead per visit is assumed to take two slots. The simulation have been performed for 10^7 points.

Results:

The simulation has been performed for three channel failure rates (0%, 5%, 10%). To change the utilization smoothly the bandwidth allocated to up-stream is changed from 15.5 to 20 Mbps, while the input traffic load is kept constant. Figure 6.6 shows the cell loss rate for the 1.5 Mbps source type. The cell loss rate of the 0.64 Mbps source type has been less than 10^{-6} in all cases and is not reported. As it can be seen the performance improvement is noticeable. In the method proposed in [117], the non-real-time traffic (0.64 Mbps sources) blocks the link due to its high burstiness, and that increases the cell loss rate of real-time traffic (1.5 Mbps sources) dramatically. The delay per cell is shown in figures 6.7 to 6.9. In the modified polling proposed in [117] the delay which is imposed on 1.5 Mbps traffic is close to the delay imposed on 0.64 Mbps traffic, while its delay requirement is much shorter. This delay brings about high cell loss rate for the 1.5 Mbps

Figure 6.6 The cell loss rate for the 1.5 Mbps source type in the non-uniform polling system and the modified polling method proposed by [117]

Figure 6.7 The delay per cell imposed on 1.5 Mbps and 0.64 Mbps sources for 0% channel failure rate

Figure 6.8 The delay per cell imposed on 1.5 Mbps and 0.64 Mbps sources for 5% channel failure rate

Figure 6.9 The delay per cell imposed on 1.5 Mbps and 0.64 Mbps sources for 10% channel failure rate

traffic type. In non-uniform polling the delay imposed on 1.5 Mbps traffic is decreased by increasing the delay of the 0.64 Mbps traffic. In fact, the performance of the system has improved effectively by considering the properties and requirements of each type of traffic, and utilizing the available bandwidth efficiently.

6.5 Considering The Effect of Channel Utilization on CFR

So far, in our analysis, we assumed the radio cell under study is isolated and didn't consider the effect of co-channel interference (CCI) on CFR, and the effect of channel utilization on CCI. In this section we modify the upper bound on utilization and the slot allocation procedure for the situation in which the CCI is present. In the second chapter we derived the following equation for the fade probability:

$$P_{fade} = 1 - \xi \cdot e^{-\frac{\chi \cdot \rho}{I_o}} \quad (6.9)$$

which can be reduced to the following equation, if $\bar{P}_r \gg T_d \cdot I$:

$$P_{fade} = (1 - \xi) + \frac{\xi \cdot \chi}{I_o} \cdot \rho \quad (6.10)$$

In these equations ρ is the channel utilization, P_r is the received power, I is the interference power, T_d is the fade threshold, and I_o and ξ are given by:

$$I_o = \frac{\bar{P}_r}{T_d} \quad \text{and} \quad \xi = e^{-\frac{T_d \cdot N_r}{\bar{P}_r}} \quad (6.11)$$

and χ is the coefficient in:

$$I = \rho \cdot \chi \quad (6.12)$$

Considering the approximate linear relation between the fade probability and the utilization and regarding the channel failure rate to be equal to the fade probability, the CFR can be written as the following form:

$$CFR \approx \phi_a + \phi_m \cdot \rho \quad (6.13)$$

where:

$$\varphi_a = (1 - \xi) \quad \text{and} \quad \varphi_m = \frac{\xi \cdot \chi}{I_o} \quad (6.14)$$

With this new *CFR*, the same technique as appendix B can be utilized to derive the upper bound on the utilization which guarantees the user QOS as:

$$\rho_G \leq \frac{G \cdot (1 - \varphi_a) \cdot \rho_o}{1 + \varphi_m} \quad (6.15)$$

where

$$G = \frac{2MTD}{2 \cdot MTD - \ln(P_{loss}) \cdot \frac{\sigma_\mu^2}{\bar{\mu}}} \quad (6.16)$$

Based on Eq. (6.15) and using the same method as we used for deriving Eq. (6.1), the C_L is obtained as below:

$$0 < (1 - \varphi_a) (1 - G) (C_L - S) + \frac{G \cdot (1 - \varphi_a) \cdot \rho_o \cdot S \cdot \varphi_m}{1 + \varphi_m} < 1 \quad (6.17)$$

Inequality (6.17) can be satisfied by:

$$C_L = \frac{1 + \varphi_m - G \cdot (1 - \varphi_a) \cdot \rho_o \cdot S \cdot \varphi_m}{(1 - \varphi_a) (1 - G) (1 + \varphi_m)} \quad (6.18)$$

Moreover, the service limit, k , is equal to:

$$k = \frac{(1 + \varphi_m)}{G \cdot (1 - \varphi_a)} \cdot (\bar{\mu} \cdot C_L) \quad (6.19)$$

and the virtual bandwidth is given by:

$$VBW = \frac{(1 + \varphi_m)}{G \cdot (1 - \varphi_a)} \cdot \bar{\mu} \quad (6.20)$$

In absence of CCI, $\phi_m = 0$ and $CFR = \phi_a$, so equations (6.18), (6.19) and (6.20) return to equations (6.3), (6.5) and (6.6) correspondingly. Using these equations, the same protocols as described in section 6.3.2 can be followed in admission control and slot allocation procedures.

6.6 Non-Uniform Slot Reservation (NUSR) Procedure

In non-uniform polling, during the polling period, the base station and the remotes should switch between transmit and receive modes frequently. Apart from the technical problems of this switching between modes, some time will be wasted in each transmission due to the excessive overhead and the transmitter power amplifier ramp. A solution to this problem may be the slot reservations at the end of each service time. In this method, the remotes, instead of making the slot requests in reply to the polling tokens at the beginning of each cycle for the same cycle, reserve the required slots at the end of each service period for the next cycle. The method uses the similar protocols and parameters as non-uniform polling, so we call it the *Non-Uniform Slot Reservation (NUSR)* method.

6.6.1 NUSR Protocols

The proposed NUSA method is described as the following:

- (1) A Basic Cycle Time(*BCT*) is determined based on the system design regarding the traffic requirements, or radio transmission requirements.
- (2) Each user declares its traffic parameters (traffic statistical characteristics, traffic requirements and its buffer contents) during the call setup procedure and whenever wants to change its type of connection.
- (3) The controller assigns a visiting period (C_L), and a service limit (k) for each user.
- (4) The same procedure as non-uniform polling is used to determine the C_L and k for each user.

The detailed description of the protocol is as the following:

In figure 6.10 the structure of a basic cycle is shown. Each *BCT* contains two sections: a short period which is called the control section and another section which contains the

Figure 6.10 The structure of a BCT in NUSR multiple access scheme

data cells and is called the data section. The first slots in the control section are used for radio signaling, channel maintenance, pilot and beacon signals, etc. Following that, a short period in every several *BCT*, depending on access delay requirement, is assigned to new connection establishment requests and replies. This period is marked by a special pilot signal. Receiving the pilot a new user sends the connection request to the base station. The request contains the information including: (1) the mean and the variance of its cell rate, (2) its *MTD* and target cell loss probability, and (3) the number of cells presenting in its buffer. Receiving the connection request, the controller calculates the user virtual bandwidth using equation (6.6) or (6.20) and accepts the request if the connection is affordable. Then the controller determines the visiting period and the service limit of the new user and starts to provide it the service in a proper *BCT*. At the end of control section, the base station broadcasts a schedule table containing the name, the order of service and the allocated slots for the remotes which are going to be served during the data section.

The data section has three parts. The first part contains the down-stream traffic, during which the base station forwards the incoming traffic to remotes within the radio cell. After the down-stream part, each remote which finds its name in the schedule table occupies the slots in up-stream part (remotes to the base) which are allocated to it according to the order and the number of cells specified in the table. At the end of service time, each remote acknowledges the base station that it has received the down-stream cells and requests the repeat if any cell is missing or erroneous. Also the remote specifies the number of cells which remains in its buffer in the last cell of the service time. Following the up-stream part, the controller broadcasts the acknowledgment of the cells received from the remotes and requests the repeat if any cell is missing or erroneous. By the end of data section, the base station has the information of all the visited queues and is able to schedule the next visit to each remote.

6.7 Comparison Between The Non-Uniform Polling and The NUSR

As we pointed out before, the basic elements of admission control and slot allocation procedures in non-uniform polling and NUSR are identical. Therefore, all the strength points which were described for the non-uniform polling are applicable for the NUSR as

well. The only difference is that the users declare the slot requests one cycle ahead. This difference brings about some advantages and disadvantages which are explained next.

6.7.1 NUSR Advantages and disadvantages

The positive points in employing NUSR over non-uniform polling are:

- 1-From the practical point of view, NUSR is more straight forward to be implemented, since the fast switch between receive and transmit modes can not be implemented in a simple way.
- 2-The overhead is slightly less than the non-uniform polling, since the polling interval at the beginning of each cycle is merged to the service times. Also, the guard time between each base and remotes transmissions are saved.
- 3-In NUSR more processing time is provided to the base station. When the reservation requests are collected, the base station has to process the collected information during the ongoing cycle and then declares the amount of service which is provided to each remote in the cycle after.

The important drawbacks of the NUSR compared to the non-uniform polling are:

- 1-Under the same visiting periods and service limits, there would be an increase in mean cell delay for each user in NUSR system. The reason is that each service request is responded one cycle later. This latency causes a serious degradation in service quality which can be overcome by doubling the visiting frequency.
- 2-The non-uniform polling takes the advantage of flexibility of polling. This flexibility can help controller to secure the control packets effectively. Since each transmission in the polling method is followed by a reception, the acknowledgments can be arranged without delay. Therefore, any impairment in the communication link can be detected fast and recovered as soon as possible. While in NUSR, any loss in "reservation packets" may cause a connection loss between the base and the remote.

6.7.2 Comparison by Simulations

To compare the performance of the NUSR and the non-uniform polling a set of simulations has been performed with the same configuration as section 6.4.2, except that the ICC is assumed to be present. The channel is modeled as Eq. 6.13 with $\phi_a = 0.03$ and $\phi_m = 0.07$, so the channel failure goes to the high of 10% as the utilization approaches one.

To see the effect of overhead reduction, another set of simulations has been carried out. In these simulations the overhead per visit for the non-uniform polling is two cells while this overhead is assumed to be one cell for the NUSR.

The results of these simulations are illustrated in figures 6.11 and 6.12. It is clear that the reservation in one cycle ahead increases the mean delay per cell. This excessive delay causes the increase in cell loss probability. The second set of simulations show better performance for the NUSR, when the overhead is reduced, but still behind the non-uniform polling performance.

In the third set of simulations the *BCT*, the polling cycles and the service limits for the NUSR are chosen to be equal to the half of the corresponding values for the non-uniform polling. The overhead is 1 cell per visit for the NUSR and 2 cells per visit for the non-uniform polling. This time, almost the same performance has been reached for the two methods.

The conclusion of these simulations is that the NUSR suffers from excessive delay due to reservation in one cycle ahead. However, the same performance as the non-uniform polling can be achieved if the inter-visit intervals are reduced to half and the overhead is decreased by 50%.

6.8 Conclusion

In this chapter the protocols of the non-uniform polling were described in details. The bandwidth allocation and admission control procedures parameters were obtained for the situation in which the CCI is present. With the same basis as the non-uniform polling, the non-uniform slot reservation (NUSR) method was introduced. To compare the NUSR and

Figure 6.11 The cell loss rate of the RTT (1.5 Mbps traffic) for the non-uniform polling, the NUSR, the NUSR with 50% overhead reduction, and the NUSR with 50% overhead and cycle limit reduction.

Figure 6.12 The average delay per cell for the non-uniform polling, the NUSR, the NUSR with 50% overhead reduction, and the NUSR with 50% overhead and cycle limit reduction.

non-uniform polling performances, three sets of simulation results were reported. The conclusion is that due to the reservation delay, the performance of the NUSR is less than the non-uniform polling. However, the same performance can be achieved for the NUSR by reducing the cycle limits and the overhead per visit by 50%.

Chapter 7

Conclusion

7.1 Conclusions

The scope of this thesis was the traffic management in ATM indoor wireless multimedia networks. The subject covers three challenging areas: broadband indoor wireless local area networks, multimedia communications, and ATM network control. Apart from channel impairments and traffic heterogeneity, another important characteristic of the system is very diverse users' quality of service (QOS) requirements. To investigate such a system one should consider the radio channel behavior along with the traffic characteristics and QOS. To do so, we considered the radio channel as an ON/OFF link, characterized by the average channel failure rate (CFR).

In the second chapter we showed that the ON periods of the channel can be modeled by exponential distribution. The OFF period characteristics depend dramatically on the techniques which are employed to mitigate fading, shadowing and interference. The effect of channel utilization on the interference power and consequently on the channel failure rate was studied in the last section of the second chapter.

Coping with the requirements of traffic management in heterogeneous networks necessitates to employ some techniques to improve performance, flexibility, and fairness of the simple polling systems. In appendix A, we presented an analytical work to approximate the pdf of the queue length of a bursty user at the polling instant, in a gated polling system, regarding the channel failures. Based on those results, we showed, in chapter 3 that the non-limited-gated polling doesn't offer good performance for the mix of bursty, sensitive to delay traffic. Since this lack of performance is due to the property of

being “non-limited”, we generalized the conclusion to other polling or reservation based methods which allocate the bandwidth as much as the user requests.

In chapter 4 the FGL polling scheme was considered. To improve the performance, non-uniform polling was proposed, and investigated by detailed simulations. Non-uniform polling was found to be superior than the uniform polling in terms of less cell loss rate and better fairness for the real time traffic. However, since the user QOS and the burstiness of the traffic were not considered in the procedure the improvement was not substantial.

Chapter 5, was appropriated to obtaining an upper bound on the utilization under which the users’ quality of service is guaranteed. This bound was obtained by deriving approximate expressions for the mean and the variance of the queue length at the polling instant for a symmetric cyclic service discipline with bursty arrivals. The obtained mean and variance were evaluated by simulations and found to be appropriate for the situation in which the system works near saturation. Also, the validity of the approximations which were used to derive the upper bound on utilization were investigated by simulations.

In chapter 6 the maximum utilization obtained in chapter 5 was utilized to determine the non-uniform polling parameters. The proper values for visiting frequency and the service limit in each visit were obtained for a given class of traffic using its mean cell rate, variance of the cell arrivals, MTD, and the target cell loss probability. Having these parameters, the bandwidth allocation protocols and the admission control procedure in non-uniform polling were presented and described in details. The effect of channel utilization on CFR were considered as well, and another set of equations for the slot allocation and admission control procedures for non-uniform polling under presence of CCI were obtained.

In the rest of chapter 6, based on the non-uniform polling design, a reservation based multiple access strategy called non-uniform slot reservation (NUSR) were suggested. The performance of the NUSR and the non-uniform polling were compared by simulations. The NUSR showed degraded performance compared to the non-uniform polling unless the cycle limits and the overhead per visit are reduced to half.

7.2 Future Research

The objective of this research was to obtain a bandwidth allocation policy, which fulfills the required performance of IBWN. To make the analysis tractable, we simplified the radio channel and the input traffic models. Then the achievements were generalized using a flexible access mechanism. More research is needed to evaluate the range of validity of the ON-OFF channel model, and to characterize the ON and OFF periods using experimental results. The work should be extended to evaluating the performance of the proposed multiple access method for other practical situations. Considering the whole system design, some other factors such as imperfect transmission of control messages, interaction between the down-link and the up-link traffic, and implementation limitations have to be taken into account. Putting the radio signalings and the fading mitigation techniques, and the multiple access mechanism together brings about additional problems which should be considered in further research.

Although the access problem in this research was investigated for a single radio cell, nevertheless, the radio link characteristics, effects of CCI from other radio cells, heterogeneity of the traffic, and guaranteeing service quality were considered. Future steps in this way can be considering the effects of handoff and the gain that can be achieved by that in the system. Doing that, one can provide a comprehensive and rather complete view of the system for a single user, such that the whole system with all of its complexity looks like a black box which is characterized by a set of parameters and equations. And from the controller point of view the system is characterized and the position of terminals and base station in the system is fairly clear. And the designer of the system, would be faced with an organized and characterized system instead of a system with many unknowns and ambiguous parameters with unrecognized interactions which can be studied only by huge simulations for particular situations.

Another suggestion for the future research is to perform similar research for a CDMA system. The research can result in a virtual bandwidth expression for a given type of traffic which is used in admission control policy. This virtual bandwidth should be obtained by monitoring the interference power in the system and investigating that whether the network resources can satisfy quality of service requirements of the new connection.

7.3 List of Contributions

The highlighted contributions of this research can be listed as below:

- studying the ON-OFF model for the radio channel, and considering the effect of utilization on channel failure rate,
- deriving an approximation for the pdf of the queue length of a bursty user at the polling instant, in a gated polling system, considering the channel failures,
- showing (analytically and by simulations) that the non-limited-gated polling doesn't present a good performance, when the communicating remotes consist of bursty, sensitive to delay sources,
- simulating the FGL polling scheme, and proposing non-uniform polling to improve the performance of the system,
- analyzing the symmetric non-uniform polling system with bursty traffic, and deriving approximations for the first and the second moments of the queue length at the visiting instant, under heavy load traffic,
- utilizing the above approximations to find expressions for maximum utilization which guarantees users' QOS requirements,
- employing the maximum utilization to derive equations for slot assignment and admission control procedures using the static parameters of the source and the channel failure rate,
- presenting a flexible access strategy for the non-uniform polling which put to use the above admission control and slot assignment procedures,
- comparing the performance of the non-uniform polling with some other schemes to show the strength points of this method,
- presenting equivalent reservation based protocol (the non-uniform slot reservation), and comparing its performance with the non-uniform polling.

APPENDIX A

A.1 The Mean Queue Length and The Mean Waiting Time at the Polling Instant for Gated Polling System with Bursty Arrivals

Regarding equation (3.10), the mean number of jobs presenting at j^{th} queue at the polling instant, $\bar{W}_j$, is equal to:

$$\bar{W}_j = \sum_{all C_{l-1}} E \left\{ \zeta_{l-1,j} + \sum_{n=1}^{C_{l-1}} \mu_{l-1,j}(n) \middle| C_{l-1} = C_{l-1} \right\} \text{Prob}(C_{l-1} = C_{l-1}) \quad (\text{A.21})$$

where $E\{./\}$ is the expectation value. Therefore:

$$\bar{W}_j = \bar{\zeta}_j + \sum_{all C_{l-1}} \bar{\mu}_j \cdot C_{l-1} \cdot \text{Prob}(C_{l-1} = C_{l-1}) \quad (\text{A.22})$$

and then:

$$\bar{W}_j = \bar{C} \cdot \bar{\mu}_j + \bar{\zeta}_j \quad (\text{A.23})$$

Defining CFR_j as the average channel failure rate for remote j , the mean number of failed slots for user j , during a cycle, would be obtained as the following:

$$\bar{\zeta}_j = \bar{W}_j \cdot CFR_j \quad (\text{A.24})$$

Substituting $\bar{\zeta}_j$ into (A.23), gives $\bar{W}_j$ as:

$$\bar{W}_j = \frac{\bar{C} \cdot \bar{\mu}_j}{1 - CFR_j} \quad (\text{A.25})$$

Using the little's law, the mean waiting time for the jobs presint in the queue at the polling instant will be obtained as:

$$\bar{D}_j = \frac{\bar{W}_j}{\bar{\mu}_j} = \frac{\bar{C}}{1 - CFR_j} \quad (\text{A.26})$$

* * *

Taking the mean value from the both sides of equation (3.9) yields to:

$$\bar{C} = \bar{S} + \sum_{j=1}^N \bar{W}_j \quad (\text{A.27})$$

where $\bar{S}$ is the mean polling overhead.

Substituting from equation (A.23) results in:

$$\bar{C} = \bar{S} + \bar{C} \cdot \rho + \bar{\zeta} \quad (\text{A.28})$$

where $\bar{\zeta}$ is the mean number of failed slots during of a cycle, and ρ is the total utilization, which respectively are given by:

$$\bar{\zeta} = \sum_{j=1}^N \bar{\zeta}_j \quad (\text{A.29})$$

and:

$$\rho = \sum_{j=1}^N \bar{\mu}_j \quad (\text{A.30})$$

where $\bar{\mu}_j$ is the mean cell arrival rate of the j^{th} source, during a time slot.

Substituting from (A.24) and (A.25), gives the mean cycle time as:

$$\bar{C} = \bar{S} - \bar{C} \cdot (\rho + \bar{\zeta}_p) \quad (\text{A.31})$$

where $\bar{\zeta}_p$ is given by:

$$\bar{\zeta}_P = \sum_{i=1}^N \frac{\bar{\mu}_i \cdot CFR_i}{1 - CFR_i} \quad (\text{A.32})$$

Define ρ' as:

$$\rho' = \rho + \bar{\zeta}_P \quad (\text{A.33})$$

the mean cycle time would be equal to:

$$\bar{C} = \frac{\bar{S}}{1 - \rho'} \quad (\text{A.34})$$

A.2 The Variance of the Queue Length at the Polling Instant for Gated Polling System

Using equation (3.36), and denoting the second term in that equation by ϑ_j :

$$\vartheta_{t-1,j} = \sum_{n=1}^{C_{t-1,j}} \mu_{t-1,j}(n) \quad (\text{A.35})$$

the variance of $W_{t,j}$ can be obtained as:

$$\sigma_W^2 = \sigma_{\zeta_j}^2 + \sigma_{\vartheta_j}^2 + 2R_{\zeta_j \vartheta_j} \quad (\text{A.36})$$

where $\sigma_{\zeta_j}^2$ is the variance of the channel failures.

Since the users experience independent radio channels, the failures are independent so:

$$\sigma_{\zeta_j}^2 = \sum_{i=1}^N \sigma_{\zeta_i}^2 \quad (\text{A.37})$$

Since the cell arrivals from different remotes are assume to be independent, the variance of ϑ_j is equal to:

$$\sigma_{\bar{v}}^2 = \overline{\bar{v}_j^2} - \bar{v}_j^2 = \frac{\sum_{n_1=1}^{C_{i-1}} \sum_{n_2=1}^{C_{i-1}} \mu_{i-1,j}(n_1) \cdot \mu_{i-1,j}(n_2) - (\bar{C} \cdot \bar{\mu}_j)^2}{C_{i-1} \cdot C_{i-1}} \quad (\text{A.38})$$

Dropping the subscribe $i-1$ from $\mu_{i-1,j}(n)$ for simplicity, the above equation can be expanded to:

$$\begin{aligned} \sigma_{\bar{v}_j}^2 = & \frac{\sum_{n_1=1}^{C_{i-1}} \sum_{n_2=1}^{C_{i-1}} (\mu_j(n_1) - \bar{\mu}_j) \cdot (\mu_j(n_2) - \bar{\mu}_j) +}{C_{i-1} \cdot C_{i-1}} \\ & \frac{2C_{i-1}\bar{\mu}_j \sum_{n_2=1}^{C_{i-1}} (\mu_j(n_2) - \bar{\mu}_j) + (\bar{C}^2 - \bar{C}^2) \cdot \bar{\mu}_j^2}{C_{i-1} \cdot C_{i-1}} \end{aligned} \quad (\text{A.39})$$

The second term of the above equation includes expectation around the mean $((\mu_j(n_2) - \bar{\mu}_j))$, which should be very small comparing to other terms, and is ignored. Expanding the first term around $\bar{C}$, leads to:

$$\begin{aligned} \sigma_{\bar{v}_j}^2 \approx & \frac{\sum_{n_1=1}^{C_{i-1}} \sum_{n_2=1}^{C_{i-1}} (\mu_j(n_1) - \bar{\mu}_j) \cdot (\mu_j(n_2) - \bar{\mu}_j) +}{C_{i-1} \cdot C_{i-1}} \\ & \frac{2 \sum_{n=1}^{\bar{C}} (\mu_j(n) - \bar{\mu}_j) \cdot CS(C_{i-1}, \mu_j) + \overline{(CS(C_{i-1}, \mu_j))^2} + \sigma_C^2 \cdot \bar{\mu}_j^2}{C_{i-1} \cdot C_{i-1}} \end{aligned} \quad (\text{A.40})$$

where $CS(C_{i-1}, \mu_j)$ is equal to:

$$CS(C_{i-1}, \mu_j) = \begin{cases} - \sum_{n=C_{i-1}+1}^{\bar{C}} (\mu_j(n) - \bar{\mu}_j) & \bar{C} > C_{i-1} \\ \sum_{n=\bar{C}+1}^{C_{i-1}} (\mu_j(n) - \bar{\mu}_j) & \bar{C} < C_{i-1} \end{cases} \quad (\text{A.41})$$

The above term is around the means of μ_j and C , so their mean value should be ignorable comparing to other terms. After few calculations (A.40) can be written as:

$$\sigma_{\vartheta_j}^2 \approx \bar{C} \cdot \sigma_{\mu_j}^2 + 2 \sum_{n=1}^{\bar{C}-1} (\bar{C}-n) \cdot R_j(n) + \bar{\mu}_j^2 \cdot \sigma_C^2 \quad (\text{A.42})$$

where σ_C^2 is the variance of the cycle time which can be obtained by the similar techniques as:

$$\sigma_C^2 = \frac{\sigma_{\zeta}^2 + \sigma_{\zeta'}^2 + \bar{C} \sum_{j=1}^N \sigma_j^2 + 2 \sum_{j=1}^N \sum_{n=1}^{\bar{C}-1} (\bar{C}-n) \cdot R_j(n) + 2 \sum_{j=1}^N CFR_j \left(\sum_{k=1}^{\bar{C}} \sum_{n=k}^{\bar{C}+k-1} R_j(n) + R_C(1) \rho \bar{\mu}_j \right)}{(1-\rho')^2} \quad (\text{A.43})$$

The terms of orders $(CFR_j)^2$ and higher in the above equation can be disregarded. Doing so, $R_C(1)$ can be obtained as:

$$R_C(1) = \frac{R_S(1) + \sigma_{\zeta}^2 + \sum_{j=1}^N \sum_{k=1}^{\bar{C}} \sum_{n=k}^{\bar{C}+k-1} R_j(n)}{(1-\rho')^2} \quad (\text{A.44})$$

where:

$$R_S(1) = \frac{(S_t - \bar{S})(S_{t-1} - \bar{S})}{\bar{C}_{t-1}} \quad (\text{A.45})$$

The last term in equation (A.36) is the correlation coefficient between $\zeta_{t-1,j}$ and $\vartheta_{t-1,j}$, which can be evaluated as:

$$\begin{aligned} R_{\zeta, \vartheta_j} &= \frac{(\zeta_{t-1,j} - \bar{\zeta}_j) \sum_{n=1}^{\bar{C}_{t-1}} (\mu_{t-1,j}(n) - \bar{\mu}_j)}{\sigma_{\zeta, \vartheta_j}} \\ &\approx CFR_j \left(\sum_{k=1}^{\bar{C}} \sum_{n=k}^{\bar{C}+k-1} R_j(n) + R_C(1) \bar{\mu}_j^2 \right) \end{aligned} \quad (\text{A.46})$$

APPENDIX B

B.1 The Mean Queue Length at the Visiting Instant for the Symmetric FGL Polling System with Bursty Arrivals

The system, in this analysis, is assumed to be symmetric, FGL polling, with bursty arrivals, and the channel failure ratio (CFR) is the same for all users. N number of queues are served during a multiplexing frame, and each one is assumed to be modeled with M number of i.i.d. ON-OFF Markov sources. Each mini source is in ON state with probability π_{ON} , producing cells with rate γ . So the probability of emitting a cell in a time slot by one of the mini sources is equal to $P_E = \pi_{ON} \cdot \gamma$. The probability of having n cell arrivals from all the sources in a “ C slots” time period is equal to:

$$P_A(n|C) = \binom{N \cdot M \cdot C}{n} P_E^n (1 - P_E)^{N \cdot M \cdot C - n} \quad (B.1)$$

and the corresponding generating function is:

$$G_B(z) = (z \cdot P_E + (1 - P_E))^{N \cdot M \cdot C} \quad (B.2)$$

Assuming that the queues are allowed to exceed their limit as long as the cycle limit is preserved, the symmetric system can be treated as a single queue system. Denoting the probability of having n_i cells, waiting in the single queue at the time that server visits the queue in cycle i , with $P_W(n_i)$, one can write the generating function of $P_W(n)$ as follows:

$$G_W(z) = \sum_{n=0}^{\infty} z^n P_W(n) = \sum_{n_{i-1}=0}^{\infty} \sum_{n_i=0}^{\infty} z^{n_i} P_W(n_i | n_{i-1}) P_W(n_{i-1}) \quad (B.3)$$

where $P_W(n_i|n_{i-1})$ is the probability of having n_i cells waiting in the queue, at the time that server is visiting the queue in cycle i , while n_{i-1} cells had been waiting at the time server was visiting the queue in cycle $i-1$. Denote the single queue service limit by K , where the limit for each of the queues in the equivalent symmetric system is $k=K/N$. Having ζ_{i-1} as the number of erroneous received cells in cycle $i-1$ due to channel failure, the above equation can be written in the form of:

$$G_W(z) = \sum_{n_{i-1}=0}^{K-1} \sum_{n_i=\zeta_{i-1}}^{\infty} z^{n_i} P_W(n_i|n_{i-1}) P_W(n_{i-1}) + \sum_{n_{i-1}=K}^{\infty} \sum_{n_i=n_{i-1}-K+\zeta_{i-1}}^{\infty} z^{n_i} P_W(n_i|n_{i-1}) P_W(n_{i-1}) \quad (\text{B.4})$$

$P_W(n_i|n_{i-1})$ can be written in terms of cell arrival probability:

$$P_W(n_i|n_{i-1}) = P_A(n_i - (n_{i-1} - W_{i-1}) | C_{i-1}) \quad (\text{B.5})$$

where W_{i-1} is the service provided to the single user in cycle $i-1$. So equation 4 can be written as:

$$G_W(z) = \sum_{n_{i-1}=0}^{K-1} \sum_{n_a=0}^{\infty} z^{n_a+\zeta_{i-1}} P_A(n_a | C_{i-1} = n_{i-1} + S) P_W(n_{i-1}) + \sum_{n_{i-1}=K}^{\infty} \sum_{n_a=0}^{\infty} z^{n_a+n_{i-1}-K+\zeta_{i-1}} P_A(n_a | C_{i-1} = K + S) P_W(n_{i-1}) \quad (\text{B.6})$$

where S is the polling overhead for the single user system, which is equal to $S=Ns$, where s is the overhead for each of the users in the corresponding symmetric system. Substituting from equation (B.1), results in:

$$\begin{aligned}
G_W(z) = & \sum_{n_{i-1}=0}^{K-1} \sum_{n_d=0}^{N \cdot M \cdot (n_{i-1} + S)} z^{n_d + \zeta_{i-1}} \left(\binom{N \cdot M \cdot (n_{i-1} + S)}{n_d} \right) \times \\
& P_E^{n_d} (1 - P_E)^{N \cdot M \cdot (n_{i-1} + S) - n_d} P_W(n_{i-1}) + \\
& \sum_{n_{i-1}=K}^{\infty} \sum_{n_d=0}^{N \cdot M \cdot (K + S)} z^{n_d + n_{i-1} - K + \zeta_{i-1}} \left(\binom{N \cdot M \cdot (K + S)}{n_d} \right) \times \\
& P_E^{n_d} (1 - P_E)^{N \cdot M \cdot (K + S) - n_d} P_W(n_{i-1})
\end{aligned} \tag{B.7}$$

Regarding equation (B.2), $G_W(z)$ is obtained as:

$$\begin{aligned}
G_W(z) = & \sum_{n_{i-1}=0}^{K-1} z^{\zeta_{i-1}} (z \cdot P_E + (1 - P_E))^{N \cdot M \cdot (n_{i-1} + S)} P_W(n_{i-1}) + \\
& \sum_{n_{i-1}=K}^{\infty} z^{n_{i-1} - K + \zeta_{i-1}} (z \cdot P_E + (1 - P_E))^{N \cdot M \cdot (K + S)} P_W(n_{i-1})
\end{aligned} \tag{B.8}$$

Taking the derivative of the above equation and evaluating the result at $z=1$, gives the mean queue length for the single queue system, at the time server visits the queue as:

$$\begin{aligned}
\bar{V} = & \sum_{n_{i-1}=0}^{K-1} (P_E \cdot N \cdot M \cdot (n_{i-1} + S) + \zeta_{i-1}) P_W(n_{i-1}) + \\
& \sum_{n_{i-1}=K}^{\infty} (P_E \cdot N \cdot M \cdot (K + S) + n_{i-1} - K + \zeta_{i-1}) P_W(n_{i-1})
\end{aligned} \tag{B.9}$$

As we explained in chapter 3, the number of erroneous slots is equal to $\zeta_{i-1} \approx CFR \cdot W_{i-1}$, where W_{i-1} is the service provided to the user in cycle $(i-1)$. Substituting ζ_{i-1} in the above equation, results in:

$$\begin{aligned} \bar{V} = & \sum_{n_{i-1}=0}^{K-1} ((P_E \cdot N \cdot M + CFR) \cdot n_{i-1} + P_E \cdot N \cdot M \cdot S) P_W(n_{i-1}) + \\ & \sum_{n_{i-1}=K}^{\infty} (P_E \cdot N \cdot M \cdot (K + S) + n_{i-1} - K(1 - CFR)) P_W(n_{i-1}) \end{aligned} \quad (B.10)$$

Noticing that:

$$\bar{W} = \sum_{n=0}^{K-1} n P_W(n) + \sum_{n=K}^{\infty} K P_W(n) \quad (B.11)$$

one can obtain the following result, after some calculations

$$\bar{V} = P_E \cdot N \cdot M \cdot (\bar{W} + S) - (1 - CFR) \cdot \bar{W} + \bar{V} \quad (B.12)$$

Regarding that $\bar{\mu} = M \cdot P_E$ and $\rho = N \cdot \bar{\mu}$, the above equation tends to the following equation for the mean service provided to the single queue, which we obtained it previously by another method:

$$\bar{W} = \frac{\rho \cdot S}{1 - \rho - CFR} \quad (B.13)$$

To obtain $\bar{V}$, we have to evaluate the second derivative of (B.8) at $z=1$:

$$\begin{aligned} \bar{V}^2 - \bar{V} = & \sum_{n_{i-1}=0}^{K-1} ((N^2 \cdot M^2 \cdot P_E^2 + CFR^2 + 2P_E \cdot N \cdot M \cdot CFR) \cdot n_{i-1}^2 + \\ & 2P_E \cdot N \cdot M \cdot S \cdot CFR \cdot n_{i-1} - N \cdot M \cdot P_E^2 \cdot S + \\ & (2N^2 \cdot M^2 \cdot P_E^2 \cdot S - N \cdot M \cdot P_E^2) \cdot n_{i-1} + \\ & N^2 \cdot M^2 \cdot P_E^2 \cdot S^2 - CFR \cdot n_{i-1}) P_W(n_{i-1}) + \\ & \sum_{n_{i-1}=K}^{\infty} ((2P_E \cdot N \cdot M \cdot (K + S) - 2K(1 - CFR) - 1) \cdot n_{i-1}^2 + \\ & n_{i-1}^2 + (1 - CFR)^2 K^2 + (1 - CFR) K - \\ & 2P_E \cdot N \cdot M \cdot (1 - CFR) \cdot K \cdot (K + S) - \\ & N \cdot M \cdot P_E^2 \cdot (K + S) + N^2 \cdot M^2 \cdot P_E^2 (K + S)^2) P_W(n_{i-1}) \end{aligned} \quad (B.14)$$

Substituting the $\bar{W}$ and ρ into the above equation results in:

$$\begin{aligned} \bar{V}^2 - \bar{V} = & \rho^2 (\bar{W}^2 + S^2 + 2S\bar{W}) + \left(\frac{\sigma_\mu^2}{\bar{\mu}} - 1 \right) \rho (S + \bar{W}) + \\ & 2\rho (K + S) (\bar{V} - \bar{W}) + (1 - CFR) \bar{W} + (1 - CFR)^2 \cdot \bar{W}^2 + \\ & 2\rho \cdot CFR \cdot (\bar{W}^2 + \bar{W} \cdot S) - 2(1 - CFR) \bar{V}\bar{W} + \bar{V}^2 - \bar{V} \end{aligned} \quad (B.15)$$

Noticing that $C_L = K + S$, the above equation can be written as:

$$\begin{aligned} 2(1 - CFR) \bar{V}\bar{W} - 2\rho C_L \bar{V} = & \rho^2 (\bar{W}^2 + S^2 + 2S\bar{W}) + \left(\frac{\sigma_\mu^2}{\bar{\mu}} - 1 \right) \rho (S + \bar{W}) \quad (B.16) \\ & + (1 - CFR)^2 \cdot \bar{W}^2 + (1 - CFR) \cdot \bar{W} + \\ & 2\rho \cdot CFR \cdot (\bar{W}^2 + \bar{W} \cdot S) - 2\rho C_L \bar{W} \end{aligned}$$

We have two unknowns in (B.16), $\bar{V}\bar{W}$ and $\bar{W}^2$, but still we can derive equations for two extreme situations:

Light Load Situation:

If the traffic load is too light, it's less likely that the queue length exceeds the limit, so the mean queue length at the visiting instant is equal to the mean service provided to the queue. Being so, $\bar{W}_{LL}^2$ can be obtain as:

$$\bar{W}_{LL}^2 = \bar{W}^2 + \frac{(1 - CFR) \frac{\sigma_\mu^2}{\bar{\mu}} \rho S}{(1 + \rho + CFR) (1 - \rho - CFR)^2} \quad (B.17)$$

So the variance of the provided service for the light load condition is equal to:

$$\sigma_{W_{LL}}^2 = \frac{(1 - CFR) \frac{\sigma_\mu^2}{\bar{\mu}} \rho S}{(1 + \rho + CFR) (1 - \rho - CFR)^2} \quad (B.18)$$

Heavy Load Situation:

For the heavy load condition where $\bar{W} \approx K$, using (B.16), the mean queue length at the visiting instant can be obtained as:

$$\bar{V}_{HL} = \frac{((1 - CFR)K - \rho C_L)^2 + ((1 - CFR)K - \rho C_L) + \frac{\sigma_\mu^2}{\mu} \rho C_L}{2((1 - CFR)K - \rho C_L)} \quad (B.19)$$

Assuming that $0 < ((1 - CFR)K - \rho C_L) < 1$, which is true when the utilization is high this term can be disregarded in nominator of the above equation. Considering that, and $K = C_L - S$, (B.19) can be written as:

$$\bar{V}_{HL} \approx \frac{\frac{\sigma_\mu^2}{\mu} \rho C_L}{2((1 - CFR)(C_L - S) - \rho C_L)} \quad (B.20)$$

B.2 The Variance of the Queue Length at the Visiting Instant for the Symmetric FGL Polling System

To obtain the second moment of the queue length at the visiting instant, the third derivative of (B.8) is evaluated at $z=1$. For the heavy load situation, using the similar techniques, the approximation for $\bar{V}_{HL}^2$ is obtained as:

$$\begin{aligned}
\overline{V_{HL}^2} = \frac{1}{3((1-CFR)K - \rho C_L)} & \left(-((1-CFR)K - \rho C_L)^3 \right. \\
& + (3\bar{V} - 3)((1-CFR)K - \rho C_L)^2 + \\
& \left(6\bar{V} + -2 - 3\frac{\sigma_\mu^2}{\bar{\mu}}\rho C_L \right)((1-CFR)K - \rho C_L) \\
& \left. + 2\left(\frac{\sigma_\mu^2}{\bar{\mu}}\right)^2 \rho C_L - 4\frac{\sigma_\mu^2}{\bar{\mu}}\rho C_L + 3\bar{V}\frac{\sigma_\mu^2}{\bar{\mu}}\rho C_L \right)
\end{aligned} \tag{B.21}$$

Disregarding the terms $((1-CFR)K - \rho C_L)$, one can approximately evaluate the variance of the queue length at the visiting instant, under high utilization, as:

$$\sigma_{V_{HL}}^2 \approx \frac{\left(\frac{\sigma_\mu^2}{\bar{\mu}}\right)^2 \rho^2 C_L^2}{4((1-CFR)(C_L - S) - \rho C_L)^2} \tag{B.22}$$

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