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Power Conservation Methods for Real-time Wireless Video Transfer Applications

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical Engineering

By

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ABSTRACT

Cellular and Handheld devices are evolving from simple feature entities into true smart devices, providing all kinds of multimedia applications and high bandwidth ubiquitous access. A key challenge is the power management of these devices, as they are battery powered and data processing and communication required by multimedia applications are extremely power hungry.

In this dissertation, the focus is to optimize and reduce power consumption for Real-time Wireless Video Transfer applications on Cellular and Handheld devices. Two important and original contributions have been made by this research work. The first is that a power management framework integrated with modules of Real-time Wireless Video Transfer applications has been proposed. The other is that a set of signaling protocols and algorithms for supporting the proposed Real-time Video Transfer Network Architecture are designed and implemented. To date, no studies have applied such power management strategies that explicitly integrate power control interfaces with wireless video transfer applications in the context of an optimal power management framework, to the author's knowledge.

In the first part of this dissertation, various power conservative design techniques from non-network related and network related perspectives have been examined. The shortcomings of current power management of operating systems for Real-time Wireless Video Transfer applications have been explained. Then, the dominant power consuming components on Mobile devices are indentified when Real-time Wireless Video Transfer applications are running. At the same time, different factors which can be used to define

the operating points and can be used in developed power control strategies have been discussed in detail.

In the second part of this dissertation, the desirable architecture of power management module has been proposed. The main functions of power management module and detailed communications between Real-time Wireless Video Transfer applications and power management strategy are implemented. The performance of power management scheme has been evaluated experimentally and analytically. Our study shows that about 44.3% power usage can be saved with the optimized power management.

In the third and final part of this dissertation, a novel integrated multi-hop cellular data network instead traditional infrastructure has been proposed. Design of a low-complexity routing algorithm to relay upstream and downstream data for this new network infrastructure has also been proposed. To further improve the power consumption of the network, a distributed layer scheduling algorithm with load balancing is discussed. In the simulation, it is shown that the proposed algorithm delivers excellent performance across a wide range of data packet parameters and configurations. The results of this research provide useful insight into optimal power management for wireless video transfer applications on mobile and handheld devices.

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Introduction

In Recent years, there has been a tremendous growth in the number and technical advancements in Cellular and Handheld devices. This includes both the ubiquitous cellular phones and also a range of information processing devices. These devices range from Personal Digital Assistant (PDAs) to more multimedia-orientated devices that play video content and MP3 music. According to a recent study by ITU (International Telecommunications Union), the number of mobile phone users worldwide is expected to soar to over 5.91 billion by the end of 2011, up from 5 billion at the end of 2010. One of the major catalysts for this growth is that the mobile phones are capable of more than just voice communication. The traditional usage model of mobile phones is changing from voice centric devices to convergence of communications, computing and entertainment. Mobile users are increasingly looking to their cellular phones being capable of sending e-mail, browsing the web, delivering video, music and 2D/3D games. In addition, mobile users want more functionality in the form of data processing capabilities, camera capabilities and “anywhere at anytime” connectivity to other devices and wireless systems.

Most of the mobile devices in the market today can already access email, surf the web and keep you in touch with friends via voice or text messages. High-end smart cellular device is adding even more to the menu. New technologies such as full-featured TVs, game console, global positioning systems, Wi-Fi functionality and video streaming are integrated into one mobile device. We can expect that this trend will be continually accelerated by two main drivers in wireless connectivity technology and mobile users’ desires for multimedia-rich applications. Typical multimedia applications in mobile devices include a variety of audio playback, video playback, still image capture, live video recording, etc. We expect more sophisticated multimedia applications such as mobile Multimedia Messaging Service (MMS), Video Conferencing, and Digital Video Broadcasting-Handheld (DVB-H) are on the way.

While mobile devices are creating more market opportunities, the increasing features and applications of tomorrow's mobile devices mean increased power and current requirements from the battery. Due to modest size and weight for mobility and portability, limited bandwidth of wireless connections, time-varying characteristics of wireless channels and limited battery power in mobile devices, providing multimedia services such as DVB-H and Video Conferencing as an adjunct to voice over Cellular and Handheld devices is a very challenging task. Just from multimedia application's point of view, the requirements of higher data rate by multimedia applications has translated into exponential growth in baseband processing requirements – from the approximate 50 MIPs required for GPRS (General Packet Radio Service) to the 200 MIPs for EDGE (Enhanced Data rates for GSM Evolution**)** to the thousands required to support 3G. Another way to look at it – going from GSM's (Group Special Mobile) 200kHz channel to UMTS's (Universal Mobile Telephony System) 5 MHz channels implies 25 times more processing. Multimedia applications have distinctive QoS (Quality of Service) and both transmit and receive diversity which requires additional signal processing. This requirement makes them extremely power hungry. Multimedia applications could degrade when battery life is low. This issue becomes even more critical when complex video coding and compression techniques are employed to support video over wireless. To achieve better video quality or higher compression gain, the video coding and compression operations are computationally intensive. This excessive processing may adversely impact the battery life. It has been realized that power consumption is forming a major roadblock while delivering high quality multimedia content to mobile handheld devices.

Unfortunately, the power supply of Cellular and Handheld device is limited to built-in battery only due to higher demand by mobile users for mobility and portability. Even worse, the physical size of mobile devices is rapidly shrinking further reducing the available space and power of the battery. Battery technology advancements over the past two decades have not kept pace with the power demands of mobile devices. Most devices use rechargeable Lithium Polymer cells which has limitations in overall lifecycle and levels of power provided. A lot of research is going on for a better battery, but they are not expected to solve the power issues over the next five years.

Therefore, power management becomes one of the most important problems in wireless communications. A large number of researchers have been trying to propose and optimize techniques for power efficient design for multimedia applications in the context of wireless environment on mobile devices in recent years. Researcher in [1][2] have presented good overviews of this topic. References [3]-[6][4] have proposed various power efficient strategies by optimizing video coding and compression. The main focus in these references is on improving either the compression ratio or encoder/decoder efficiency of H.264, H263 or MPEG-4. Several other interesting power efficient designs on hardware level (CPU, hard-drive, DRAM, LCD etc) can be found in [7]-[9]. These papers [10]-[11] address the power conservation issues from the network perspective by proposing new protocol and control strategies at different layers such as MAC, data, network and transport. However, an interesting disconnect is observed in the research activities undertaken at each level mentioned above. Power-conservative techniques developed at each computational and communicational level have remained seemingly independent of each other. There are potential opportunities for substantial improvements achievable through cross-level integration. It is observed that the joint performance of an aggregation of techniques at various levels has received relatively little interest. The cumulative power gains observed by aggregating techniques at each stage can be potentially significant. We can reduce energy consumption by designing strategy of efficient power utilization in the system with no limitation on individual components. Further, there are certain assumptions that may not be applicable by taking into consideration the unique hardware architecture of Cellular and Handheld devices. We have observed also that power management strategies addressing the power efficiency based on mobile computers and operation system running on them may not work efficiently anymore for multimedia application scenario. It is highly application dependent because the processors in Cellular and Handheld devices are running most of the time and there are seldom chances for AP (application processor) to go into sleep mode. In addition, the workload characterization of multimedia applications on Cellular and Handheld devices has not been carefully studied yet. Therefore, in order to further improve power consumption of multimedia applications, especially on Cellular and Handheld device, we have to make more efforts for developing a flexible power management architecture and making a balance between computation and communication costs to achieve overall power conservation.

In this dissertation, we contribute a power management architecture to overcome the aforementioned limitations of existing solutions. This technique is integrated with software and hardware optimization for improvement in power savings. With additional tangible benefits, the proposed framework provides power efficient solution in the context of Real-time Wireless Multimedia applications targeted to Cellular and Handheld devices, specifically

(i) Energy usage of each component in the context of Cellular and Handheld device is investigated. The bottleneck components in terms of power consumption when Multimedia application is running are also identified.

(ii) The workload characterization of threads of multimedia application under different combination of frequencies and voltages of application processor (AP) is experimentally studied. These results are used to drive our power consumption optimization efforts at each software and hardware level.

(iii) An aggressive power management system architecture is proposed; each thread of multimedia application to corresponding optimized operating points is fine tuned. The algorithm for switching operations with minimum power cost is also presented.

(iv) A novel routing and signaling protocol for both uplink and downstream between base station (BS) and mobile devices for power conservative integrated multi-hop network topology is designed.

Finally, we measure the power and evaluate performance of the proposed integrated approach in improving power efficiency on the experimental platform with real-time video conferencing implementation. The novel routing and signaling protocol is simulated in the constructed model using Matlab.

The measurement results indicate that the management strategy can save as much as 17%-25% power consumption from the system perspective. Additionally, the layered scheduling algorithm achieves the expected load-balancing even in extremely complicated traffic environment.

This dissertation is organized as follows. Chapter 1 introduces the subject and summary of the work accomplished in this dissertation. Chapter 2 presents a survey of earlier researchers' work in the context of how it relates to this dissertation. Several experiments including AMR-NB audio stream encode and decode, H.264 video streaming encode and decode with different hardware configurations to study multimedia application and power trade-offs have also been examined. Chapter 3 discusses the system architecture of Real-time wireless multimedia application with aggressive power management in detail. It also discusses how each thread of application communicates with power management (PM) module and how operating points get switched with minimum power cost. Load-balanced routing algorithm is described in Chapter 4. In this chapter, analytical and simulation results for percentage of traffic assigned to each routing note (RN) with different inter-arriving time and packet lengths have been presented. Chapter 5 concludes the summary of the contribution of this research and discusses the applications of this work. A discussion of practical issues in the application of the results to power efficient design of Multimedia Applications on Mobile devices, and directions for future research work are presented.

Chapter 2

Background and Related Work

In order to turn mobile devices into entertainment equipments with all kinds of multimedia capabilities, the advancements in wireless communication and computing technology are extremely important. When power optimization is concerned, the research works on power-conservative technologies are respectively divided into two corresponding categories: network-related and non-network-related.

In this chapter, the background for this dissertation and a survey of related work in the literature are provided. According to level of our work, the survey is focused on technical challenges that remain in the area of power-efficient network architecture, routing algorithms of wireless network and power management of hardware and Operating System (OS) in general. Other specific works are referenced in the subsequent chapters as required.

2.2.1. Brief History of Wireless wide-area Networks

The canonical model of wireless network is cellular network, which mainly provides voice-oriented service and low-rate data service. This traditional wireless network can provide Internet access for mobile devices but it cannot support enough bandwidth required for Multimedia applications. Mobile operators worldwide are accelerating to deploy Universal Mobile Telecommunications System (UMTS) wireless network in Europe and Code division multiple access (CDMA) 2000 wireless network in America, promising high-rate packet data network and ubiquitous access to IP-based broadband multimedia applications to mobile users. Next generation mobile technologies (4G) such as Worldwide Interoperability for Microwave Access (WiMAX) and 3rd Generation Partnership Project (3GPP)-Long term evolution (LTE) have been available on the market since 2006 and 2009, respectively. With new wireless network technologies, connection is almost instant and mobile users can have 'always on' connectivity to network.

The first commercial radio telephony network was made available to mobile users by the Bell Telephone Company in the early 1950's. The main drawback of this network was that only a limited number of people could be served by the network. In 1982, the Conference of European Posts and Telecommunications developed the Global System for Mobile Communications (GSM), which introduced Digital radio telephony and is widely deployed standard today. General packet radio service (GPRS), which is also called 2.5G network, is an enhancement to GSM networks with further support for packet radio. The GPRS overlays a packet-based air interface on the existing circuit switched network. It provides a packet core primarily for data applications. Packet switching allows radio resources to be shared efficiently by a large number of users since radio resources are allocated if there are data to be sent or received. The UMTS is the evolution of GSM systems and is called 3G mobile system. The biggest change from 2G to 3G systems is that 3G systems offer higher bit-rate support for packet data services. The LTE, the successor of 3G, is expected to provide a comprehensive and secured all-IP based solution. With support for packet data built into the air interface as well as the core network, multimedia applications for the mobile industry are made possible and implementable. Table 2. 1 shows a comparison among 2G, 3G and 4G cellular wireless transport networks.

Table 2. 1 2G- 3G and 4G Cellular Wireless Transport Network

Transport Technology	Data Rate	Frequency Band	Channel Access
GSM	9.6 kbps	850MHz,900MHz, 1.8GHz,	FDMA/TDMA
GPRS	Up to 115 kbps	850MHz,900MHz, 1.8GHz,	FDMA/TDMA
EDGE	Up to 384 kbps	850MHz,900MHz, 1.8GHz,	FDMA/TDMA
W-CDMA (UMTS)	Up to 2 Mbps	850MHz, 900MHz,1.7GHz,1.9GHz	CDMA
CDMA2000 1xEV-DO	Up to 2.4Mbps	400MHz, 800MHz,900MHz,1.7GHz, 1.8GHz,1.9GHz, 2.1GHz	CDMA
LTE	100Mbps	700MHz,1.8GHz, 1.9GHz,2.6GHz	OFDMA/MIMO/SC_FDMA

In the cellular networks, land based bridges, known as base stations, are used to provide connectivity. A cellular or handheld device within this network directly communicates with the base station whose coverage area (i.e. cell) includes the location of this device. With the coordination of base station, power control in those packet cellular networks was mainly focused on adjusting the transmission range to reach various receivers [12]-[15].

However, the inability of existing cellular networks to scale to high data rates and to cope with the accelerated growth in wireless user devices has prompted researchers and the communication industry to explore alternative network solutions.

2.2.2. Wireless LAN Network

WLAN is a computer network covering a limited area, like an office, group of buildings. It utilizes spread-spectrum technology based on radio frequency typically in the 2.4GHz or 5GHz unlicensed band to support high data rate wireless communication and user mobility. This technology is becoming popular, especially with the rapid emergence of new small portable Cellular and Handheld device with wireless network interface card. The major WLAN standards today are the *IEEE* 802.11 family, which currently includes six over-the-air modulation techniques that use the same protocol. The most popular previous standards are *IEEE* 802.11a, 802.11b and 802.11g amendments to the original *IEEE* 802.11. *IEEE* 802.11n is the latest amendment, which is published in 2009. A summary of the *IEEE* 802.11 standards is provided in

Table 2. 2.

The *IEEE* 802.11 specification defines two types of operational modes: infrastructure mode and ad hoc (peer-to-peer) mode. In infrastructure mode, all mobile and wireless clients communicate with wireless base stations (access points), which offers the connection from the wireless air interface to the hard-wired Ethernet network. The access point converts *IEEE* 802.11 packets to *IEEE* 802.3 Ethernet LAN packets. Data packets traveling from the LAN to a wireless client are converted by the access point into radio signals and transmitted out over a range of several hundred feet through walls and other non-metal ceilings. All wireless clients and devices within range can receive the packets, but only those devices with the appropriate destination address will receive and process the packets.

Table 2. 2 *IEEE* 802.11 standard family

Protocol	Data Rate (Mbits/s)	Op.Frequency (GHz)	Modulation	Range (Meters)	Release Date
802.11	1, 2	2.4-2.5	DSSS,FHSS		1997
802.11a	6, 9, 12, 18, 24, 36, 48, 54	5.15-5.35/5.47-5.725/5.725-5.875	OFDM	~30	1999
802.11b	1, 2, 5.5, 11	2.4-2.5	DSSS	~100	1999
802.11g	1, 2, 5.5, 6, 9,11, 12, 18, 22 24, 33, 36, 48, 54	2.4-2.5	OFDM	~30	2003
802.11n	200,540	2.4 or 5	MIMO	~50	2009

A basic wireless infrastructure with a single access point is known as a Basic Service Set (BSS). When more than one access point is connected to a network to form a single sub-network, it is called an Extended Service Set (ESS). The *IEEE* 802.11 specification includes roaming capabilities that allow a mobile user to roam among multiple access points on different channels. Thus, roaming users with weak signals can associate themselves with other access points with stronger signals like a cellular phone system. Figure 2. 1 shows the architecture of Wireless Local Area Network with an Infrastructure BSS (from http://www.answers.com/topic/wireless-lan).

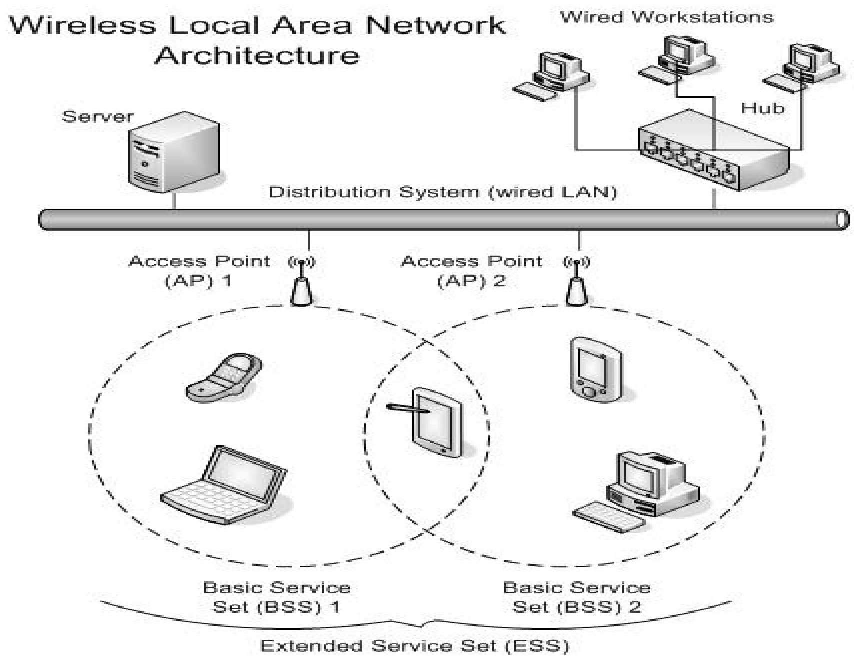


Figure 2. 1 Wireless Local Area Network Architecture

In ad hoc mode, all of the mobile devices within range of each other can discover and communicate directly via radio waves without involving an access point. Ad hoc mode is convenient in the areas where there is little or no communication infrastructure and existing infrastructure is expensive or inconvenient to use. In order to transmit a message beyond the range of a mobile device, this device must rely on one or more intermediate devices to relay the messages to its final destination.

2.2.3. Network-Related Power-Saving Techniques

Considering power-conservative issues of above two wireless networks, infrastructure mode can use central Base Station or Access Point to coordinate mobile devices for transmission power control and other power management algorithm. Without such central coordination, power-efficient designs pose more challenges for ad hoc networks. During the past decade, lots of research activities have been focused on Medium Access Control (MAC) layer, network-layer and higher-layer implementations.

In Open Systems Interconnection model (OSI model), the MAC layer is a sub-layer of the data link layer right above the physical layer. The MAC layer is mainly responsible for access scheduling of shared medium. According [16], a device's power consumption strongly depends on the MAC protocol adopted. In [10], the authors propose a Distributed Contention Control (DCC) protocol. Based on the slot utilization and number of transmission attempts, DCC estimates the probability of successful transmission before each frame is actually transmitted. If the probability of success is low, the transmission is deferred to reduce the potential retransmission overhead. Otherwise, the frame is transmitted immediately. The increase of the packet loss probability and many unnecessary retransmissions consume significant communication power. Through observing the channel congestion level, battery energy is saved and unnecessary retransmission is avoided. The proposed DCC is compatible with the *IEEE* 802.11 Distributed Coordination Function (DCF) mode. The author suggests implementing DCC between the physical and the MAC layers. The DCC protocol can temporarily suspend the transmission of frames with low success probability. In addition, a Power Save DCC (PS-DCC) is further proposed in [18]. The author incorporated the energy concerns into transmission decision making by deriving another evaluation formula. This mechanism is reported to yield quasi-optimal power consumption in ad hoc networks. Further summaries on crucial design principles of low-power MAC protocols for ad hoc networks can be found in reference[11].

Going up above the MAC layer in network layer, five metrics for power-aware routing are proposed in [20]. With time to network partition be maximized, the total power consumption can be reduced by further minimizing energy consumption for each packet, the variances of hosts' power levels and maximum node cost. However, minimizing maximum node cost tends to select routes around congested areas which may sacrifice the lifetime of the network. Reference [21] proposes a distributed algorithm to maximize battery drained-out time at each host by balancing the energy draining rates among all hosts proportional to their energy resources. Different from [20], this work has transmitter power control integrated into the routing protocol and there are multiple transmission levels available.

Residing above the network layer, more innovative approaches implement power management strategies by proposing new architectures for wireless communications. The author of [22] presents multihop cellular network (MCN) to preserve the benefit of conventional single-hop cellular networks (SCN) where the service infrastructure is constructed by fixed bases. It also incorporates the flexibility of ad-hoc networks where wireless transmission through mobile stations in multiple hops is allowed. MCN is claimed to reduce the required number of bases or improve the throughput performance, while limiting path vulnerability encountered in ad-hoc networks. In [23], the congestion problem due to unbalanced traffic in a cellular system is addressed and the interoperability for heterogeneous networks is provided. Integrated cellular and ad hoc relaying systems (ICAR) increases the system's capacity cost and also reduces the transmission power for mobile hosts by efficiently balancing traffic loads between cells. Simulation results show that the blocking/dropping probability in a congested cell and the overall system can be reduced with a limited number of ARSs and some increase in the signaling overhead as well as hardware complexity. To achieve further balanced network traffic, several load-balanced routing strategies are implemented in references [24]-[26]. While significant attention has been paid to energy consideration in MAC protocol, network layer and new ac, the issue of power savings at application layer, especially for multimedia application over such wireless network architecture has received only limited attention.

In this dissertation, we propose real-time video transfer network architecture (RVTNA), which extends the model of multihop cellular network. In this optimized network architecture, routing nodes (RN) have shorter transmission distance. It means a lot of power saving for mobile devices when multimedia applications have heavy video data traffic. The architecture, corresponding signaling protocols, routing strategy and a new distributed layer scheduling algorithm of RVTNA has been discussed in detail in Chapter 5.

2.2.4. Non-network power-saving Techniques

Application processor (AP), which acts like a central processing unit (CPU) of desktop or laptop PC in Cellular and Handheld devices, determines the speed and range of those devices' processing power. The computing power of a unit is generally measured in mega-hertz (MHz) or giga-hertz (GHz) range.

Most of APs used in Cellular and Handheld devices are fabricated in CMOS processes. The power dissipated by CMOS structures is composed of two factors: dynamic and static power dissipation. Dynamic power dissipation results from the active switching of the transistors' logic state. In contrast, static power dissipation occurs because of the current that leaks from the transistors while they're powered.

For static power dissipation, the main contributors are the applied and the threshold voltages of the transistors in the circuit. Of course, the silicon manufacturing process also has a huge influence on the overall power that is dissipated. The main contributors to the dynamic power dissipation of CMOS structures are: applied voltage, operating frequency and switching-structure capacitance. In the active state, well over 90% of the total power dissipation of AP can be approximated by:

$$\mathrm{Power} = \alpha C V^2 f \qquad (1)$$

where α is the transition activity dependent parameter, C is the switched capacitance, V is the supply voltage, and f is the clock frequency [26][27][28].

Reducing any of the terms in above equation (1) can save the overall AP power consumption and extend mobile device's battery life. Recently, significant developments and research efforts have been made on Dynamic Voltage Scaling (DVS) [28] [29] [30][31].

We observe a fact that peak performance is achieved from running AP at the highest clock frequency and corresponding voltage levels. However, it is rare that an application needs an AP's maximum performance all the time. For some time intervals, this unused extra performance represents wasted power. In this dissertation, we focus on matching AP's active operating level to the Real-time performance requirements of the Wireless Video Transfer application.

Other than AP, various hardware components -LCD display, Image sensor, Ram, and Nand Flash are used in mobile devices to support multimedia application. In order to get more aggressive power savings, power management of those individual components is also considered in this dissertation.

The Operating Systems (OS) running on mobile devices evolve very fast and more functions are implemented for power management of the system and peripheral components in every new release as power issues of those devices become critical. Windows Mobile devices have several predefined power states: on, Backlightoff, userIdle and off. Mobile devices can transit among those power states depending on system configurations [33]. For Linux-based devices, several modes of operation are supported. Devices can switch among Run mode, Idle mode and Sleep Mode. The structures and mechanisms are implemented by following advanced configuration and power interface (ACPI) [34]. However, it is hard to reach the most power efficient mode for Wireless Video Transfer application by utilizing OS's Power Management Framework. When Wireless Video Transfer application is running, mobile device will stay "on" and never enter Sleep mode, which is the most power saving mode.

In order to overcome such limitation, we propose new power management strategy to achieve even more aggressive power savings. We intend to adjust the frequency and voltage in the power equation (1), which represents potential areas of power savings. However, we realize that it is not always true that the power optimization is achieved by setting AP at the lowest frequency and voltage which meets the application performance requirement from system perspective. Many other factors like other components of the device and application specific information are necessary to be included when selecting power optimized operating point of the system. Since power consumption and performance metrics are application dependent, it is vital for wireless video transfer application to pass its processing requirement to the new power management strategy. In order to gather this information, we defined the model of wireless video transfer application and collect the character of the application through a few cases in next Chapter.

Chapter 3

System Architecture of Cellular and Handheld Device and Real-time Wireless Video Transfer Model

The cellular and handheld devices have unique hardware architecture compared to personal computer. In order to run real-time wireless video transfer application and achieve the maximum power efficiency on such architecture, the predominant internal components that contribute most to the power consumption need to be identified. Then, simulations of four cases are implemented to collect the stochastic characteristic of system performance. Based on the analysis of the experiments' result, we get the knowledge about AP utilization and specially the corresponding power consumption. We also find out the factors which can be utilized in our power optimization strategy. In the following sections, the popular components used in current cellular and handheld devices are briefly introduced.

3.1 Cellular and Handheld device technology

It is important to note that the market of cellular and handheld device is moving very fast. With new products being regularly introduced, users can see the continual improvements in underlying components such as memory devices, LCD displays and storage devices.

3.1.1 Application processors

Application processor provides the computing power for cellular and handheld devices. As processors speed increases, cellular and handheld devices can process the extended range of applications and allow extra hardware features to operate. Current feature phone and smart-phone on the market can have AP running at frequency from 108MHz to 2GHz.

3.1.2 Memory

Read-only memory (ROM) chip is mainly used in cellular and handheld devices. It stores basic software programs (address book, calendar, notepad and operating system) and remains intact even when the machine shuts down. Random Access Memory (RAM) is used to temporarily store data while processing applications and as the long-term file store for documents, pictures etc. The size of RAM ranges from 8 MB to 1024MB. Flash memory is a new widely used memory technology and quickly becoming the standard nonvolatile memory choice that also allows stored data to be saved even when the memory was disconnected from power supply. The big advantage of flash memory over ROM is that no separate device is needed to modify its content. There are two major technologies of Flash memory: NOR and NAND. NOR Flash memory provides high-speed random-access capabilities, being able to read and write data in specific locations in the memory without having to access the memory in sequential mode. NOR Flash allows the retrieval of data as small as a single byte. NOR Flash is good at applications where that data is randomly retrieved or written and most often found built into cellular and handheld device to store the operating system. NAND Flash is named after the specific mapping technology used for data (Not AND). NAND Flash memory reads and writes in high-speed, sequential mode, handling data in small, block sizes. NAND Flash can retrieve or write data as single pages, but can’t retrieve individual bytes like NOR Flash. The NAND Flash is commonly found in cellular and handheld device for data storage.

3.1.3 Expandable memory and Input and Keyboards

An Extra (expandable) memory can be plugged into a mobile device through an expansion slot. Media applications that store and process digital images and audio files require the use of such expansion. Micro SD is mainly used in current devices and its storage size has a range up to about 32GB.

A large number of cellular and handheld devices use a stylus-based input system for handwriting recognition. A virtual keypad is displayed on the display screen, which can be tapped with the stylus. There are a few handheld devices with built-in QWERTY keypads.

3.1.4 Display and Connectivity with Bluetooth and WiFi

Most of the cellular and handheld devices use a typical size about three to five inches color screens. Industry recommends a minimum of QVGA (320*240) screen resolution, which is the important feature with regard to display quality. LCD screen is based on thin-film transistor (TFT) technology which provides a good display surface both indoors and out. A backlight for illumination is provided for indoor use.

Bluetooth and WiFi are widely found in cellular and handheld devices to replace cables and are used to connect to a network or printer, or to handset. Bluetooth allows devices to communicate over short distance up to 10m using low bandwidth wireless connections at speeds of typically 56 to 721 kb/s while WiFi provides a higher wireless connection at speed of 2 to 200Mbps.

3.1.5 Cameras, Music and OS

By integrating a sensor which captures RAW image data, digital camera are becoming more and more popular with the release of many new models of cellular and handheld devices. With the development of camera phone technology, most devices provide 1.2 to 12 mega-pixel still image capture and video record capability. Video clip play back is supported in a variety of formats e.g. Moving Picture Experts Group (MPEG), Audio Video Interleave (AVI).

MP3 audio play back with build-in voice recording is commonly found in mobile devices. AC’97 is a very popular audio controller which supports features like independent channels for stereo Pulse Code Modulated (PCM) in, stereo PCM out, surround PCM out, center/LFE PCM out, MODEM out, MODEM in and mono Mic-in. Audio formant includes WMA, MP3, AAC, AAC+ etc.

Most cellular and handheld devices are presently based on one of the five major operating systems (OS):

- Linux (android, ios, meego)
- Symbian Operation System
- Blackberry Operation System
- Windows Mobile
- Palm OS

3.2 The hardware model and software model of Real-time Wireless Video Transfer System

In this dissertation, we establish hardware model of cellular and handheld devices as shown in Figure 3. 1. It is a close abstraction of current popular hardware components.

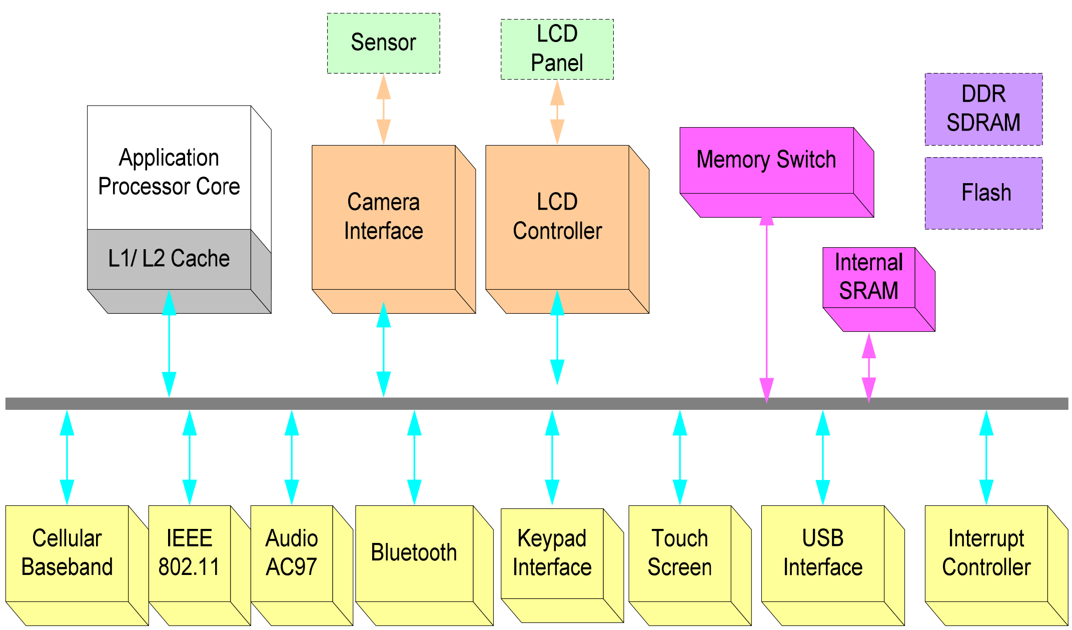


Figure 3. 1 Hardware Architecture of Cellular and Handheld Devices

The software model of Real-time Wireless Video Transfer System is depicted in Figure 3.2. The application has been broken into low level functional units. There are four main modules: video encoder, video decoder, audio encoder and audio decoder on both server and client side. The following is a brief description about how application works. First, client initiates the application and sends the request to the server. Video encoder gets input from camera component while audio encoder gets input from microphone. Both video and audio encoder output the data to the transmitter buffer. The video and audio decoders take input from receiver buffer and output data to LCD display and speaker. The corresponding video and audio modules follow the same process on server side. The client and server communicate over the wireless interface through communication processor.

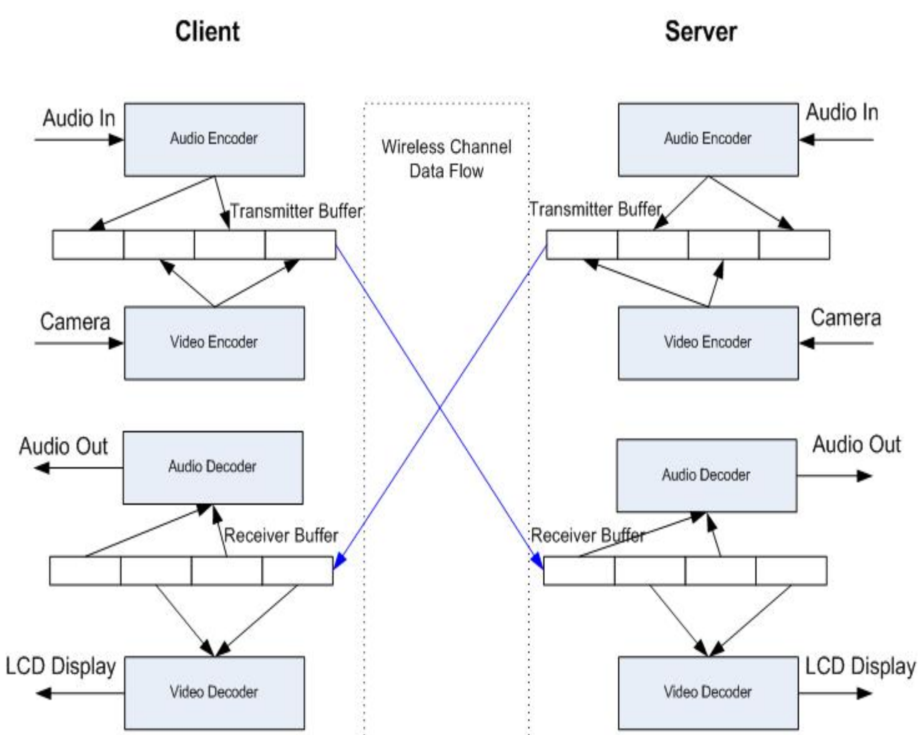


Figure 3.2 The model of Real-time Wireless Video Transfer System

3.3 Power Consumption by Components in Cellular and Handheld devices

The first step in developing a power-efficient Real-time Wireless Video Transfer system is to identify which components in the architecture of cellular and handheld devices are bottlenecks in terms of energy consumption. Some components may be more amenable for power improvements than others. Studies show that the significant consumers of power in a typical mobile PC are the microprocessor, liquid crystal display, hard disk, system memory, keyboard/mouse, CDROM drive, I/O subsystem, and the wireless network interface card [35][36]. In order to get power consumption data of Cellular and Handheld devices, we have measured power consumption of each component on our development board. The result is shown in Figure 3.3. The whole system is sampled by running on Windows Mobile operating system and OS is in idle mode. Idle mode means there is no other customer's application running at the same time while we measure the power. The pie graph demonstrates that nearly 42.14% of power consumed is by AP, 19.32% by the LCD, 16.17% by Memory. If we change the OS to run mode by running video recording/playback and audio recording/playback with file transferring through the network interface card (NIC) or GSM channel, the power consumed by NIC or Communication processor and Radio Frequency (RF) would increase dramatically. The communication module may consume 18% of total system power with heavy in/out data traffic. However, this is not always the case because the hardware configuration might be different. Further, the measurement results nevertheless illustrate the importance that energy conservation needs to be considered in components such as AP, LCD, Memory, NIC and Communication processor and RF. Consequently, we mainly focus on AP, NIC and Memory on hardware level when we optimize power conservative strategy for Real-time Wireless Video Transfer systems.

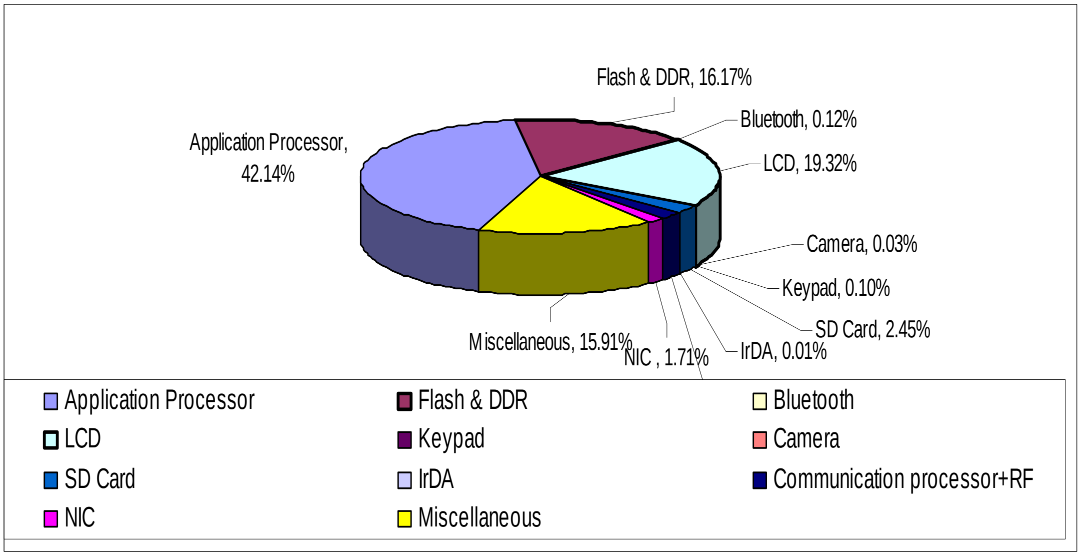


Figure 3.3 Power Consumption of Components of cellular and handheld device

3.4 Power Management of AP

The AP on our development board has features of changing Core Frequency of AP among 104MHz, 208MHz, 416MHz, 624MHz and 806MHz and setting Core Voltage at 1.0V, 1.1V and 1.375V. For Real-time Wireless Video Transfer, we want to find out the best operation point in terms of power consumption. The operation point is defined as the combination of settings for different components. For now, we only care about the Core Frequency and Core voltage of AP. We have implemented three video and audio playback experiments with different Core frequency and voltage settings. These experiments are simulations of video and audio encoder and decoder of Real-time

Wireless Video Transfer system. Other than AP Core voltage and frequency, we turn on/off L2 cache in case 4 to see the impact of L2 cache for memory power optimization.

Case 1:

The development board is booted up with Windows Mobile 5.0 for Pocket PC and play audio clip in WMA (Windows Media Audio) format and video clip in WMV (Windows Media Video) format. WMA is the windows media format from Microsoft Corporation. It enables audio files smaller than MP3 –and better sound quality. WMV is a generic name for the set of video codec technologies which are also developed by Microsoft. The reason we choose these two audio and video formats is that Windows Media player embedded in Windows Mobile 5.0 supports both WMA and WMV. In experiment, both audio and video contents are played separately on AP at the fixed Core Frequency 208MHz, 416MHz and 624MHz. The purpose of doing this is to compare the differences of CPU utilization on different Core Frequency points for both WMA and WMV playback. There is another program sampling performance data from the AP. CPU utilization is calculated based on these sampled data. Figure 3.4 shows the result of CPU utilization of WMA and WMV playback on different Core Frequencies of AP. It is noticed that WMA playback occupies 16.51% of CPU at Core Frequency 208MHz and 10.12% of CPU when we double the speed of CPU to 416MHz. The value of CPU utilization for WMV drops 43% from 30.42% to 17.19% and finally to 12.31% at the Core Frequency as 208MHz, 416MHz and 624MHz respectively as shown in Figure 3.4. The results show that the CPU utilization is not linear with the Core Frequency of AP for both WMA and WMV playback. .

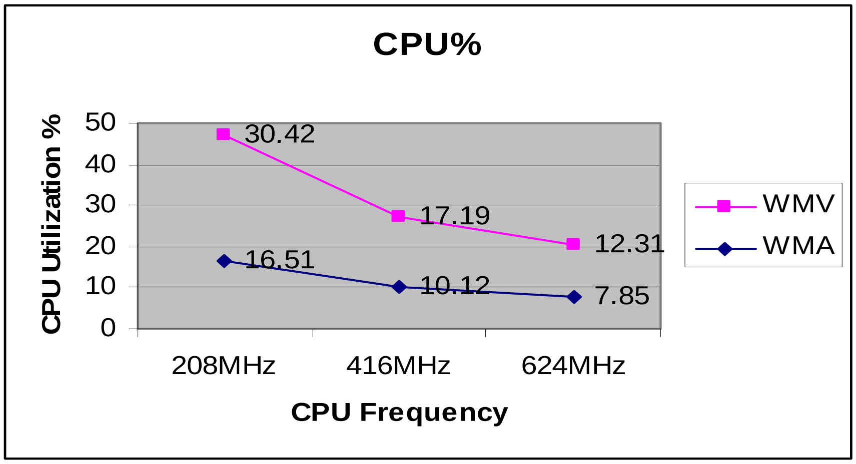


Figure 3.4 CPU Utilization of WMA and WMV Playback on Different Core Frequencies

MIPS (Million Instructions per Second) is another way to measure the processor's speed. We calculate the overhead in MIPS and the result are shown in Figure 3.5. The data demonstrates that the most efficient operating point is 208MHz for both WMA and WMV from MIPS's perspective. As shown in the graph, WMA takes 34.34 MIPS to finish the audio playback and WMV takes 63.27 MIPS to finish the video playback at 208MHz, which is the lowest overhead achieved by comparison with the Core frequency 408MHz and 624MHz.

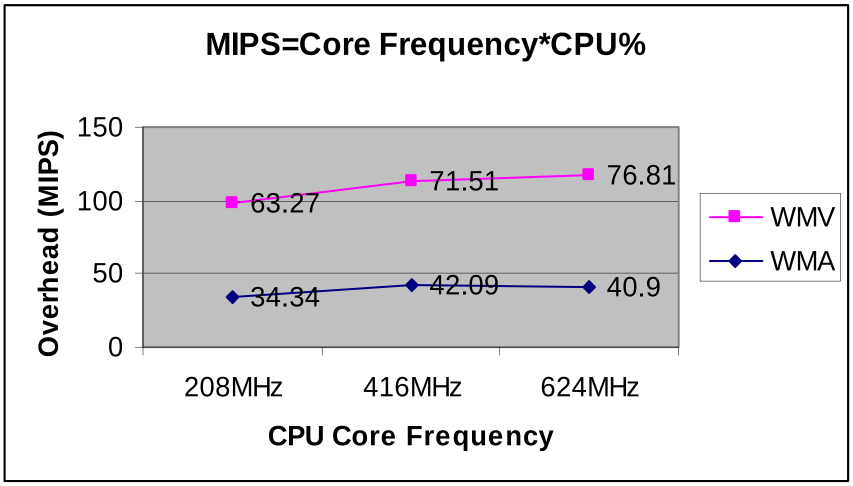


Figure 3.5 Overhead in MIPS of WMA and WMV Playback on Different Core Frequencies

Case 2:

In experiment 2, we run a video testing program with different parameters for video size, which are QVGA (320*240) and QCIF (176*144). Those two video sizes are commonly supported by most of Cellular and Handheld devices. The testing program includes sub-functions like video capture, video format transfer, video raw data encode and video encoded data decode plus display. The video capture is implemented directly by using the image sensor coming with the development board. The decoded video is displayed on the LCD panel which comes with the development board. The program runs at fixed Core Frequency of AP at 416MHz. We use the same monitoring program used in experiment 1 to collect the performance data. This time the program samples the percent of CPU usage by each sub-function. To see the effect of parameter "Bitrates" of video content, we compare the percent of CPU usage by each sub-function with different Bitrates values for each video size. Table 3. 1shows the CPU usage by each sub-function at frequency 416MHz with video size QVGA. The parameter of "fps" is the frame rate of the video content. We play the video at speed of 15 frames per second. The CPU usage by each sub-function at frequency 416MHz with video size QCIF is shown in

Table 3. 1 AP Usage-QVGA 15fps at Core Frequency 416MHz

Sub-Function	384Kbps	256Kbps	192Kbps
Video Capture	0.1%	0.1%	0.1%
Video Format Transfer	8.8%	8.8%	8.8%
Encode	40-53%	26-41%	28-37%
Decode+Display	13-15%	12.5-13.5%	12%
Total	62-77%	48-65%	49-56%

Table 3.2 AP Usage-QCIF 15fps at Core Frequency 416MHz

Sub-Function	128Kbps	96Kbps	64Kbps
Video Capture	0.1%	0.1%	0.1%
Video Format Transfer	4%	4%	3.6%
Encode	9-12%	9-11%	8-10%
Decode+Display	4.6%	4.3%	4.2%
Total	18-21%	16-20%	16-18%

From the measurement results shown in above table, we note that the small variations with Bitrates change are not significant on CPU utilization. The total percent of CPU usage changes from 62-77% to 49-56% while the Bitrates changes from 384Kbps to 192Kbps for QVGA. The percent value changes even less for QCIF because the minimum value of percent of CPU usage changes from 18% to 16% while Bitrates changes from 128Kbps to 64Kbps. We notice the video dimension is the key factor that dominates the CPU usage. The total CPU usage reduces from 62% to 18% when the video size switches from QVGA to QCIF. The CPU usage is proportional to the power consumption. In other words, if a program occupies more CPU usage, it consumes more power. Based on this experimental result, video size is a better candidate than bitrate for power optimization.

Case 3:

The third experiment concerns power consumption with different Frequencies of AP when we run the Windows Media Player to play WMA and WMV. Figure 3.6 shows the value of total power consumed by the device versus different frequencies. We see that at frequency 416MHz the whole system consumes 210.18 (mW) for WMA and 234.536 (mW) for WMV, which are the lowest power values by comparing with 221.23 (mW) for WMA and 243.52 (mW) for WMV and 350.32 (mW) for WMA and 373.06 (mW) for WMV, which are values of power consumption at frequency 208MHz and 624MHz. It means the longest battery life for the Cellular and Handheld devices if we run audio and video playback at Core Frequency of 416MHz. Please note, in this experiment, the size of WMV format we test is QVGA. The best power efficient operation Core Frequency of 416MHz can only apply to QVGA. We also observe that if we change the size of the Video content, the best power efficient operation Core Frequency changes too.

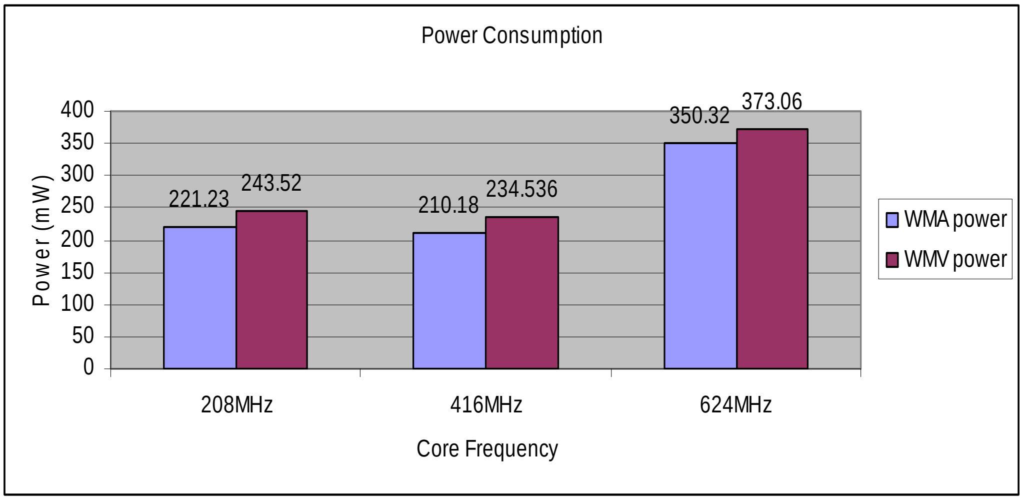


Figure 3.6 Core Frequency vs. Power Consumption

Case 4:

The last experiment studies the impacts of L2 cache on performance for audio decode and video decode. L2 Cache is a short for level 2 cache. It has the same purpose as L1 cache. L2 cache is a small amount of high-speed memory packed within the same module with the CPU chip. The L2 cache feeds the L1 Cache, which feeds the CPU. L2 Cache can provide faster CPU access to instructions and data in memory, thus increasing system performance. L2 Cache can be disabled on the system boot up, which reduces the power consumption of the system. From the power performance of the system perspective, we need to find out the trade-offs for efficiently utilization of L2 Cache. We start by running H.264 decode and AMR-NB decode.

H.264 is a block-oriented motion-compensation-based codec standard. It was developed by a Joint Video Team (JVT) from the Moving Picture Expert Group (MPEG) and the ITU-T's Video Coding Experts Group (VCEG) in late 2001 [37][38]. The primary goals of H.264 were improved coding efficiency and improved network adaptation. The syntax of H.264 typically permits a significant reduction in bit-rate [39] compared to all previous standards such as ITU-T Rec. H.263 and ISO/IEC JTC 1 MPEG-4 Visual at the same quality level [40][41].

Adaptive Multi-Rate Narrowband (AMR-NB) GSM is a speech codec with 4.75 - 12.2 bit rate range. Based on code excited linear predictive (ACELP) model, the codec is fully compliant with the ETSI GSM 06.90 specification. This speech coder is mainly used for toll quality speech compression in the 2nd+ generation mobile telephony. The real-time video wireless transfer would use the same H.264 codec and AMR-NB codec. It is why we evaluate the performance of both codec in Case 4.

For both H.264 decoding and AMR-NB decoding, we measure the percent of CPU usage under two L2 Cache configurations (L2 Cache on and L2 Cache off). Both of these configurations are separately simulated at low and high Frequency of 208MHz and 624MHz. The measured results are shown in

Table 3. 3. We have also compared the differences between L2 Cache off and L2 Cache on. The performance improvements calculated are listed under column of L2 Cache benefits. We notice that audio codec time has 2.5% improvement and video codec time has 12 % improvement with L2 Cache enabled at Core Frequency 208MHz. The values of improvement of audio codec time and video codec time increase to 8.8% and 30.6% if we change the setting of the Core Frequency from 208MHz to 624MHz. The difference between the impacts of L2 Cache on video and audio is that the video decoding tends to be more memory bound while audio/speech decoding tends to be more CPU bound. An application is generally considered CPU-bound when most of its execution time is spent on computation, using the data and instructions loaded in D-cache

and I-cache. The schedule instructions suitable to the underlying processor architecture (reducing stalls) can potentially increase performance of CPU bound applications. These applications tend to keep the CPU busy all the time and the processor idle time is negligible. An increase in processor frequency (and in turn voltage) helps to increase the performance of these applications. Generally, if the performance of an application is a linear function of CPU frequency, it is a CPU bound application. In order to meet performance requirements, it is essential to have these applications run at the maximum possible frequency. Some applications that work on large data blocks (greater than the cache size) usually have to access data outside of the caches, and become bound by the memory or the system bus speed. These applications, such as a memory copy, move large blocks of data and tend to generate significant memory traffic, with most CPU cycles being lost while waiting for data. In such cases, the performance does not improve even if the speed of the CPU is increased as the performance is a function of the memory speed. From result shown in Table 3.2, it is observed that that audio decode is CPU bound and video decode is both CPU and memory bound. It is better to turn on L2 cache when AP is handling video related processing.

3.4 Summary

In this chapter, we have identified the main power consumption components in Cellular and Handheld device architecture. Four cases have been considered to find out the characteristics of video and audio modules. The power effect of Core Voltage and Frequency, video size, Bitrates and L2 Cache is evaluated. The power management designed in next chapter is going to use these factors to yield a more efficient management strategy.

Table 3. 3 L2 Cache Impacts on Audio and Video Codec Performance

Core Freq (MHz)	L2 Cache Off				L2 Cache On				L2 Cache benefits		
	CPU%	MIPS (MHz)	Codec Time (ms)		CPU%	MIPS (MHz)	Codec Time (ms)		MIPS	Audio Codec Time	Video Codec Time
			Audio	Video			Audio	Video			
208	42.16	87.69	0.81	10.28	37.83	78.69	0.79	9.05	10.3%	2.5%	12.0%
624	22.60	141.02	0.34	5.17	17.40	108.5	0.31	3.59	23.0%	8.8%	30.6%

Chapter 4

Integrated Power Management with Real-time Wireless Video Transfer application

4.1 System Architecture

This chapter describes the proposed power management (PM) for the real-time wireless video transfer applications. The high-level architecture with integrated PM is depicted in Figure 4. 1. As an extra added module, PM works parallel in software model of real-time wireless video transfer application. PM manages all modules of real-time wireless video transfer application and other hardware components at the same time. With this PM framework, communication cost and computation overhead is reduced and system power efficiency is also improved.

The following main functions have been implemented in the power management modu*l*e:

- Sampling of idle time of the system and monitoring the performance requirements,
- Dynamic scaling the frequency and voltage of AP
- Dynamic power management of peripheral components of Cellular and Handheld devices
- Make optimal power management strategy for the whole system
- Communicate with OS and handle transition among operating points

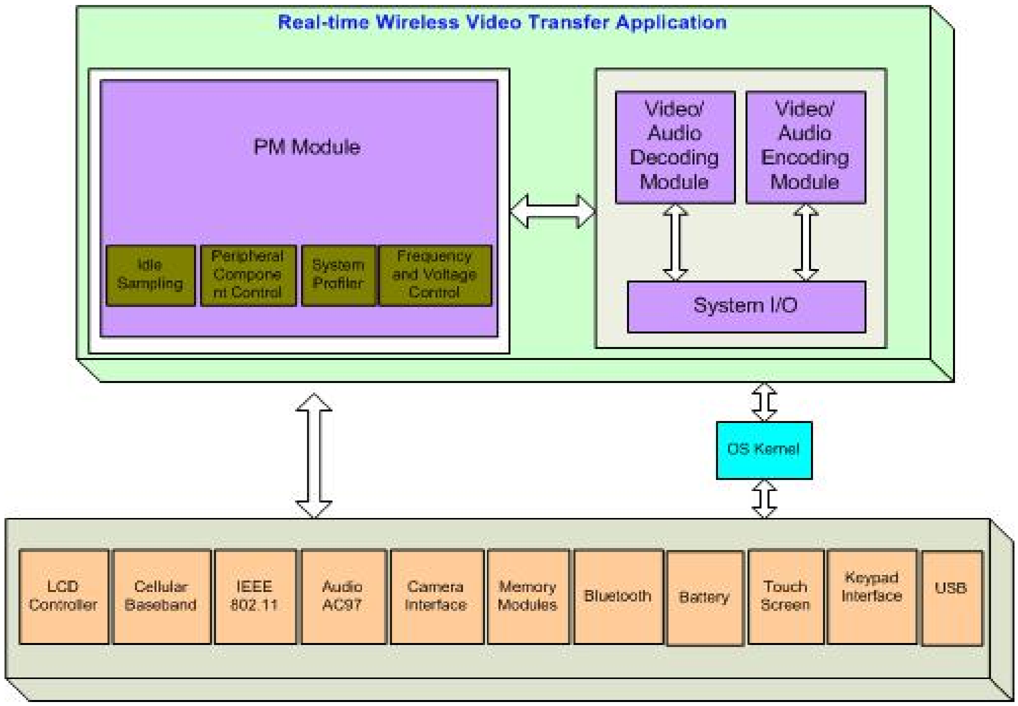


Figure 4. 1 Software Architecture of Real-time Video Transfer with Power Management

4.1.1 Idle Sampling and Performance Profiler of System

In order to match application's performance requirement with appropriate AP frequency and voltage, PM needs to monitor instantaneous performance demands by each module of Real-time Video Transfer application on the fly. There are two special sub-functions implemented in the PM for this purpose. The first function is named Idle Sampling. It determines the instantaneous performance demands of each module by assessing the idle time of the system, which is represented by the time that the AP spends in the idle state. It is perfect choice to provide AP usage information because the idle thread is executed when the OS is not busy. However, since the idle thread only executes when there is no task ready for running, the information is only provided when the AP is used less than 100 percent of the time. In cases where AP usage is less than 100 percent of the time, but still very high, interrupt service route (ISR) is used as a backup to provide AP usage information. Based on the collected data, the information that how busy the system was is known. Then, PM exploits this information and adapts its power strategy accordingly. Figure 4.2 shows the work flow of an idle sampling process. At the beginning of system idle, the idle sampling component starts the timer counting. Then, the system calls idle function to put AP into idle mode. Once the system exits the idle mode, the timer counting is stopped and idle sampling component aggregates idle time and records the value to a pre-defined global variable. The second idle sampling component timer ISR is triggered every $T_{idle\_sampling}$ second. The $T_{idle\_sampling}$ is the length of sample window time for the system timer. This system timer is initialized and starts right after the idle sampling function is started by PM. Once the system timer fires and the interrupt is identified, ISR component performs the utilization analysis. Then, it signals the PM to access the analysis result. Based on the calculated utilization during the sampled window, if PM finds out that system is busy or opposite, it makes decision to change AP to higher or lower operating frequency. Utilization thresholds can be used to control when to signal the PM. In the simulation of PM, the value of thresholds and $T_{idle\_sampling}$ are designed to be able to adjust dynamically based on the next scheduled running modules of real-time wireless video transfer application.

The second function is called system profiler, which monitors the system as shown in Figure 4.3. There are 5 main events to be tracked. The details of events are described in Table 4. 1. This monitoring process allows PM to track the real-time data traffic of AP core, dynamic memory, internal SRAM, system bus and peripheral bus. For each scheduled Video/Audio encoding and decoding module, the access of dynamic memory, internal SRAM, system bus and peripheral bus does not remain static at any given time. This dynamic traffic characterization of memory and bus usages is essential as supplement for PM to evaluate system status. By using system profiler, PM is able to get up-to-date traffic information appearing on memory bus, system bus and peripheral bus. System profiler is designed as event driven and it automatically alerts the PM when the system state needs to be changed.

Table 4. 1 Events Monitored by System Profiler

Events monitored	**Usage for Event**
Core Read/Write Latency Measurement	Instruction Traffic
System Bus Request(Length of time that at least one bus request is asserted on System bus)	Image Capture Traffic and LCD display traffic
Dynamic Memory Queue Occupied (number of cycles when the dynamic memory controller queue is not empty)	% Memory Used
Internal SRAM Queue Occupied (number of cycles when the internal memory controller queue is not empty)	% Memory Used
Peripheral Bus Request(Length of time that at least one bus request is asserted on Peripheral bus)	Network I/O Traffic, Audio I/O Traffic

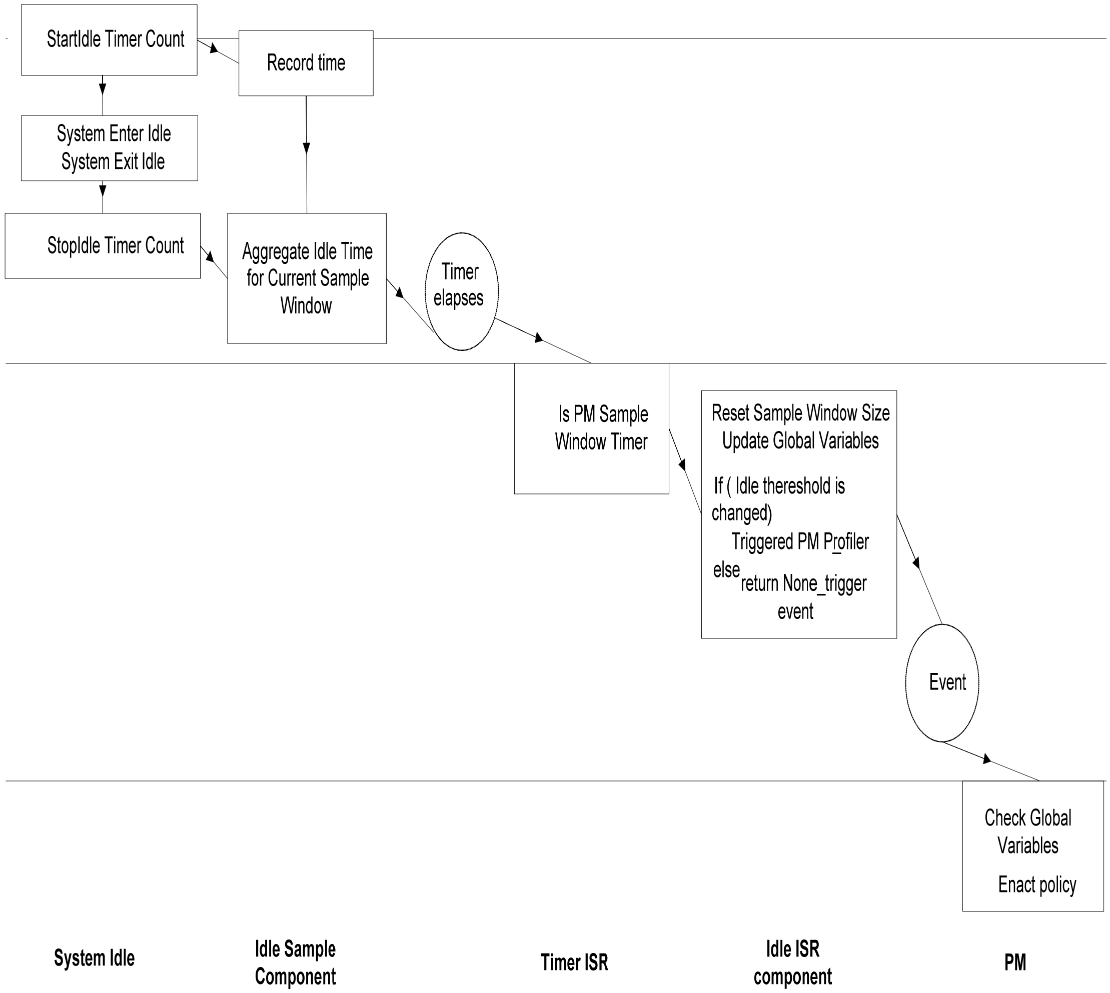


Figure 4.2 Work Flow of Idle Sampling Process

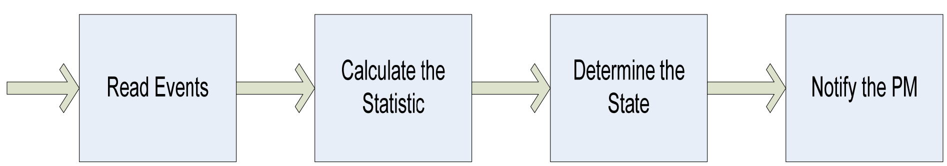


Figure 4.3 System Profiler

4.1.2 Configuration of Operating Points

At any given point in time, the Cellular and Handheld device with real-time wireless video application running executes at a particular status. This particular status encapsulates a set of inter-dependent, physical and discrete parameters that define a specific system performance level. The system here includes both AP and peripheral components. The interest is particularly focused on system performance level along with an associated energy cost. Based on the specification of hardware, multiple statuses supported by the hardware platform are defined. These statuses are referred as operating points and are used as the lowest-level objects in PM. In the following sections, the system power consumption associated with an operating point is represented by $P_{\_N} : \{OP\_N\}$, where OP_N is operating point N.

The selection of physical parameters for the configuration of operating point is dependent on the specification of hardware platform by the nature of operating point. These parameters are inter-dependent in most of the combinations. The relation between voltage and frequency of AP is a good example of inter-dependency. The voltage of AP usually limits the maximum operating frequency of AP. Similarly, the frequency of AP cannot be considered without also considering the voltage. As other discrete parameters like video size, bitrates, and cache sizes examined in Chapter 3, they are also critical for selection of operating point from multimedia application's perspective.

The detailed configuration of operation points used in this dissertation is listed in Table 4. 2. It is a combination of hardware platform and application related parameters. The parameters from the application are video size and bitrates. AP voltage, AP frequency, system I/O bus frequency, internal SRAM frequency, caches status and LCD refresh frequency come from AP specifications and peripheral components.

Peripheral components connected to AP have their own power states. These power states can be classified by the power consumption and they affect the system performance also. Thus, power status of peripheral components is included when parameters for the definition of an operating point are selected. However, it does not mean that an arbitrary combination of the power states of the components can define an operating point. The following concerns are carefully considered when the rules how PM should manage the peripheral components are designed.

Table 4. 2 Examples of Operating Points

Physical Parameters	Value range	Units
AP core voltage	1.0,1.175,1.375	Volt
AP core frequency	75,104,208,312,416,624,806	MHz
LCD	104,156,208	MHz
Internal SDRAM	156,208,312	MHz
System I/O Bus	104,156,208	MHz
Video size	320*240,352*288,176*144	Pixel
bitrates	384,256, 192, 128, 96,64	Kbps
caches	On/off	

4.1.3 Power Management of Peripheral Device

As explained earlier, the definition of operating point needs to be at the system level. It includes power status of both AP and peripheral component devices. The external peripheral component devices on the development board have a tremendous influence on system-wide energy consumption. Peripheral component devices are competitive just like AP and must be able to deliver peak performance when required. But they are not required to be always in the active state. The ability to enable and disable peripheral devices, as well as of tuning their performance to real-time wireless video transfer application is the key incentive in energy-efficient PM design. However, the scenario becomes quite complicated when the appropriate peripheral device power status of an operating point is selected. It has to be considered very carefully. For example, the LCD interface controller of AP uses a frame buffer which can be stored in external SDRAM or internal SDRAM. The size of internal SDRAM is only 768k bytes. If the required size of frame buffer is bigger than 768k, it is needed to use external SDRAM as frame buffer. When the LCD controller is enabled, then any valid operating point for the system must specify a memory bus frequency high enough to satisfy the refresh rate of the display.

One of the responsibilities of PM is to respond the changes in peripheral component device states. PM relies on low-level device drivers to aggressively manage the power consumption of the peripheral component devices. For example, if a user does not currently produce input data on touch screen, the device driver of touch screen can power-down the touch screen controller unit as well as lower the on-board clock or remove the clock from the touch screen controller. It is profitable for system-wide power utilization.

It is noted that individual peripheral component device does not have the global view of the system. The information about other peripheral component devices has to be provided by PM to completely specify the operating point. PM manages all sets of constraints associated with each peripheral device. For example, the LCD controller may specify the pixel clock rate of 156MHz, which the value can vary from 104.0MHz to 208.0MHz. This means the system timing configuration and the memory-bus bandwidth can't be lower than 156MHz. Otherwise, visible video artifacts can be observed. At any given point of time, the PM needs to check constrains list of peripheral component devices to avoid entry to such invalid operating points.

The constraints of peripheral component devices are just part of the issue. PM has to handle cases like one component serving multiple tasks at the same time. For example while audio is doing playback, the audio decoding module takes several milliseconds to decompress the audio data of one second and enters sleep after that. Let us assume a different task with "idle" mode to be scheduled next time. If this task doesn't require Direct Memory Access (DMA), PM still can't decrease the frequency of DMA engine because AC'97 controller continues transfer such audio data from SDRAM to audio device via DMA. It means DMA has to run at a specific frequency or higher during the whole period of audio decoding sleep. To solve this problem, PM treats those peripheral component devices statistically. No matter the audio or video playback is running or not, PM maintains real-time states of peripheral component device and their power states. PM does not put related components into inactive state in such scenarios.

4.1.4 Change of System Modes

The operating system running on Cellular and Handheld devices has been modeled as a state machine in this dissertation in general. Figure 4.4 illustrates the transition between different states in this model. At any given instant, the system stays at a certain state. Then, it moves through different states in response to the following events:

(a) tasks are scheduled

(b) the system goes idle

(c) interrupts are received and handled

These system states are referred as system modes. When system stays in the run mode, there may be several tasks running in the scheduling tasks pool at the same time. The scheduler in the OS kernel makes decision which task is scheduled to run next. Given the case of real-time wireless video transfer application, the main tasks scheduled to run in Run mode are Video/Audio encoding, decoding modules and system I/O modules. System I/O process handles encoded video and audio data from the transfer and receiver buffers and are implemented as separate modules. Each system mode is associated with different operating points specific to the requirements of the application. After operating points are configured, PM controls the system by the designed Rules and mechanisms and moves the system from one operating point to another. The main idea of this control mechanism is to set operating point in response to changes in real-time wireless video transfer application's activity and optimize power consumption at the same time.

The main motivation is that significant system-wide energy savings can be achieved by reducing AP frequency and voltage, Memory frequencies, System I/O bus frequency and LCD refresh frequency while the system is idle. Further, it is noted that it is profitable sometime to adjust operating point even while the system is in run mode. However, it requires an aggressively implemented PM to specify different operating points between run and idle mode. PM needs to manage the transition smoothly and efficiently.

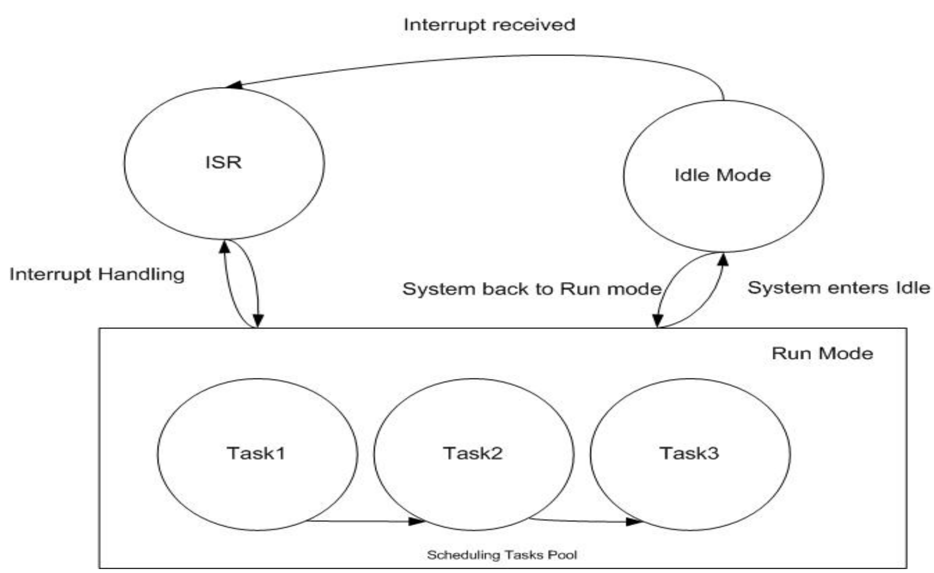


Figure 4.4 System Modes and Transitions

The architecture of mode change for the real-time wireless video application is illustrated in Figure 4.5. As we can see, run mode has multiple tasks waiting to run. Run mode and Idle mode are treated differently because Idle mode has no task to run. When the system is in Run mode, several operation point pools are defined. Each pool is dedicated to a task and normally should have a set of operating points in it. Every operating point is fine-tuned with a bundle of preset system parameters and performance requirement by that task. The system power consumption associated with operating point can also be calculated by measuring the current of the board. *When a thread is scheduled to* run, PM decides which operating point is to be associated with this task. Note that, each task is generally allowed to have any number of operating points because fine-grained control over the power states of the system can be achieved with more choices of operation points. Figure 4.5 shows an example pool associated with encoding thread. It has four operating points in that pool. Whenever encoding thread is the current running thread, the Cellular and handheld device can be at one of operating points. An operating point with detailed settings for AP voltage (1.375V), AP frequency (624MHz), LCD refresh frequency (208MHz), SDRAM frequency (312MHz), and System I/O bus frequency (208MHz) is shown in the middle. It specifies an example operating point for the encoding task with all other peripheral devices enabled. For Idle mode, there is no pool but the system can have multiple operating points for low power consumption purpose. For example, system can stay at 624MHz idle mode or 208MHz idle mode. If the system can be put into 208MHz idle mode, the power consumption can be significantly lower than 624MHz idle mode.

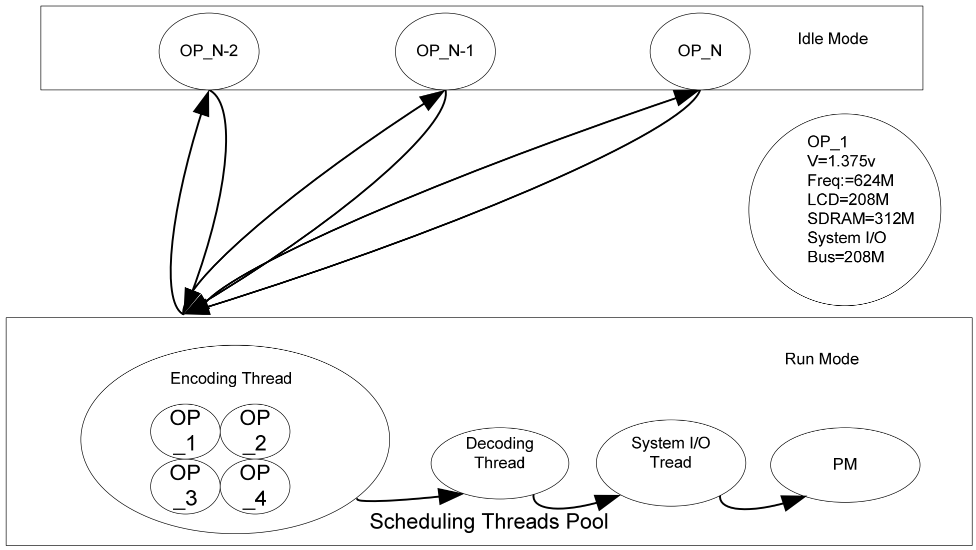


Figure 4.5 Architecture of modes change with multiple operating points

4.1.5 The transition cost

Another important characteristic of transition between operating points is that switching has a cost. For the sake of simplicity, the cost is defined in terms of delay. In practice, because of the physical limitations of the AP and peripheral component devices, switching between different operating points takes many steps. It includes not only saving AP's context, but also saving context of peripheral component devices which should be done through device driver. For example, to set a new AP frequency and voltage, PM first uses Inter-integrated circuit (I2C) driver to communicate the new voltage value to Power Integrated Circuit (IC). Then, power IC unit uses dynamic voltage management unit to control the physical settings for the specified voltage. After the voltage is stable, the frequency is changed through dynamic frequency management unit on the AP side. The AP on development platform can scale frequencies with a latency measured in a few microseconds. It is necessary as the voltages vary in tens of microseconds. This is to be done without interrupting system operations. A transition is not instantaneous and components on chip are not operational during a transition. System performance is lost whenever a transition between operating points is initialized. There is also a transition power lost if power consumption is concerned. Transition costs have to been considered when more aggressive and finer-grained control strategy polices are designed for PM. Excessive costs may make one or more low-power operating points almost useless because it is very hard to amortize the cost of transitioning in and out of them.

For example, consider the transition between two operating points, as shown in Figure 4.6. Putting a device into operating point 2 (OP_2) includes a period whose duration is the sum of the actual time spent in OP_2 ($T_{\_op\_2}$ and the time spent to enter and exit it (T_{enter} and T_{enit}). For the sake of clarity, we define the power consumption for an operating point (denoted by $P_{\_op\_n}$), power consumption during the center (denoted by P_{enter}) and power consumption during the exit (denoted by P_{exit}).

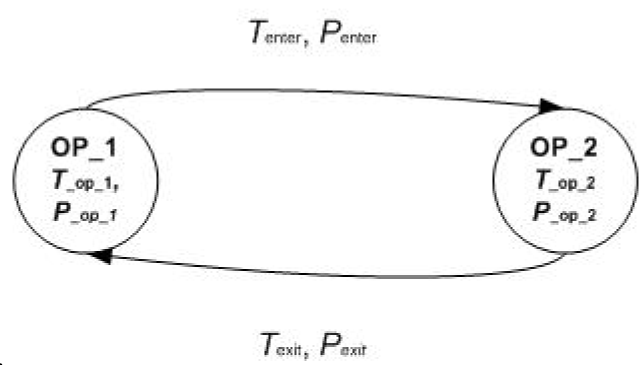


Figure 4.6 Delay of Transition between Two Operating Points

If a task is scheduled to run for the next period T_{next}, the PM decides which operating point to enter or stay at original operating point unchanged based on the following algorithm.

The break-even time is defined for an operating point OP_N (denoted by T_{BE_N}) as the minimum time required to compensate the cost of entering operating point OP_N. If $T_{next} < T_{BE\_N}$, it means there is not enough time to enter and exit next operating point. PM achieves no performance penalty for real-time wireless transfer application system. The system is only allowed to enter the next operating point when the workload of computation of the task scheduled in next period T_{next} can also be completed if system enters new operating point. In this case, T_{next} needs to be greater than the sum of two terms: the total transition time i.e., the time required to enter and exit the new operating point and the time that has to be spent at new operating point. Otherwise, system stays at the old operating point.

With respect to the system power, the break-even power is defined as P_{BE_N}. It can be calculated by

$$P_{BE\_N} = P_{OP\_1} - (P_{enter} + P_{exit} + P_{OP\_2}) \tag{4.1}$$

Where P_{OP_1} and P_{OP_2} are the power consumption of system staying at old operating point and new operating point, respectively. If $P_{BE\_N} < 0$, there is no power saved by entering next operating point, which means power consumption of the device P_{op} at old operating point is smaller than the sum of two terms: total power transition loss and power consumed when system enters in new operating point.

In summary, for the example shown in Figure 4.4, the PM changes the system to new operating point only when the following two conditions are met:

(1) P_{BE_N}>0, there is a power utilization benefit

(2) $T_{next} > T_{enter} + T_{exit} + T_{OP\_2}$,

For our system with multiple operating points, T_{BE_N} and P_{BE_N} are calculated for each paired operating points. A tradeoff between T_{BE_N} and P_{BE_N} has to be made for each operating point to obtain smaller values of T_{BE_N} and higher power efficiency.

4.2 The implementation of PM

The simulation of Real-time Wireless Video Transfer application is developed in C language. The main modules are implemented as corresponding threads. A thread of execution is the smallest unit of processing that can be scheduled by an operating system. Before PM is implemented, it is needed to make sure the operating pool for each thread has been pre-fine-tuned. As prerequisite, every operating point in the pool can meet performance requirement by each thread. It is of immense importance to guarantee that all computation hard deadlines can be met for every module at any operating point in its dedicated operating point pool. If the delay in response time is too long and user have bad experience, the frequency and Voltage of AP for that operating point is not acceptable. For example, the simulation only have operating points with AP frequency set at 208MHz, 416MHz, and 624MHz for decoding thread. Although, the AP on development board also supports 75MHz and 104MHz.But these frequencies are eliminated as the candidate operating points because Video frame is lost by running at these two frequencies.

4.2.1 Registration

PM Initially starts itself as a system service, which runs in the background during system boots up. A global variable *PM _ running* is defined. It is set to the value of true after PM is finished loading. Then, PM sends broadcast information to all loaded peripheral component drivers for its existence. All loaded peripheral component drivers which support PM start registration process as the response. For peripheral component device which supports hot-plug features, the de-registration to PM is necessary and is used when device is un-plugged. When system exits, all remaining peripheral component devices go through the same de-registration process. The registration/de-registration process is shown in Figure 4.7.

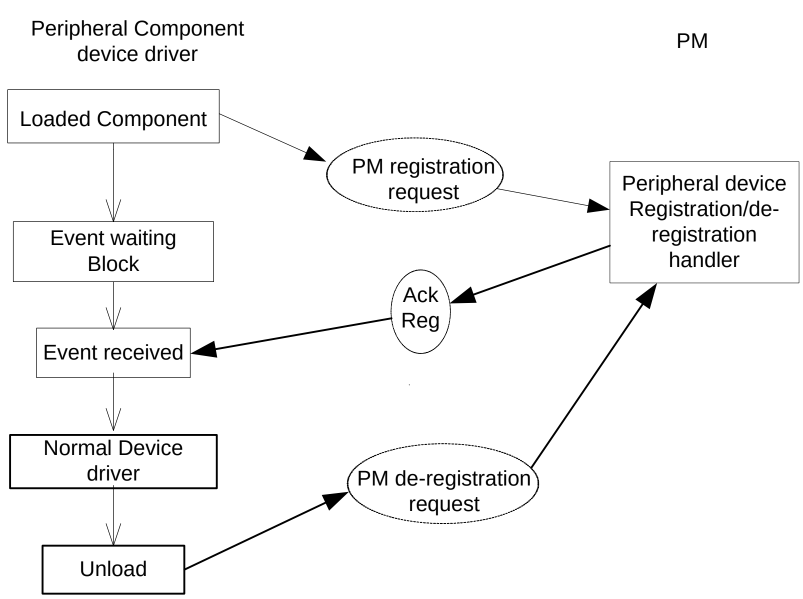


Figure 4.7 Loaded Peripheral Component device driver registration/de-registration to PM

During the process of registration, the driver of peripheral component device must provide its constraint information to PM. Peripheral component devices specify their requirements as sets of constraints associated with particular device states. For example, the LCD driver specifies the pixel clock in the range of 104 to 208 MHz while active, and no constraint while inactive. The peripheral component devices must inform PM of their frequency and state sensitivity so that PM can notify peripheral component device of a pending state transition when applicable. An extra interface is also implemented. It allows the peripheral component drivers to supply a callback function directly to PM. There are many components which have their own power management strategy. When PM decides to switch to low power states, PM can use those callback functions to let peripheral components take over to enter their own low power state. Wireless LAN components are good examples of such scenario. Usually, wireless LAN component supports standby, sleep, normal, ultra-low power modes. The driver of wireless LAN component wraps those features and provides resume and suspend function to the upper layer. So, it is better to handle the power mode switching at device driver level for such component device. PM utilizes such flexibility through this callback mechanism.

Both registration/de-registration are implemented as blocking function. It means the drivers are waiting until acknowledge event from PM are received or time-out happens. There is no acknowledge event sent back from PM as a response for de-registration request. It is noted that all constraints that the component drivers impose on PM are no longer valid after de-registration is completed. When peripheral component devices change state to inactive, the constraints imposed on PM also become invalid during that inactive period. If the registration succeeds, PM would return success message to peripheral component driver. Otherwise, it returns an error code. After successful registration, PM maintains a list which stores all registered peripheral components. The design of this list is to provide PM with the ability to notify peripheral component drivers when power parameters change. This notification allows peripheral component drivers to prepare for the pending transition, or to veto the transition if necessary.

4.2.2 Implementation of PM functions for each module of Real-time Wireless Video Transfer application

The operating pool information configured for each module of Real-time wireless video transfer application is sent to PM right before the corresponding thread starts. It is similar to registration process in sub-section 4.2.1. After all the pool information is passed through successfully, the name of module and available corresponding operating points are stored in an array and maintained by PM. At the beginning of the thread, the following functions are developed to communicate with PM.

1) Ready_Op_Change

2) ChangeFrequencyBlock

3) ChangeFrequencyBlockRelease

4) SetMiminumOp

5) SetMinumumOP_Release

With video decoding thread as an example, it calls block function Ready_Op_Change to inform PM that video decoding is scheduled to run and ready for operating points switch. If PM decides to change operating point, it sets new operating frequency and sends acknowledge back to video decoding thread. PM might decide to keep the same operating point while the video decoding thread continues to run at the same operating point after it gets feedback from PM. The request frequency change process is shown in Figure 4.8.

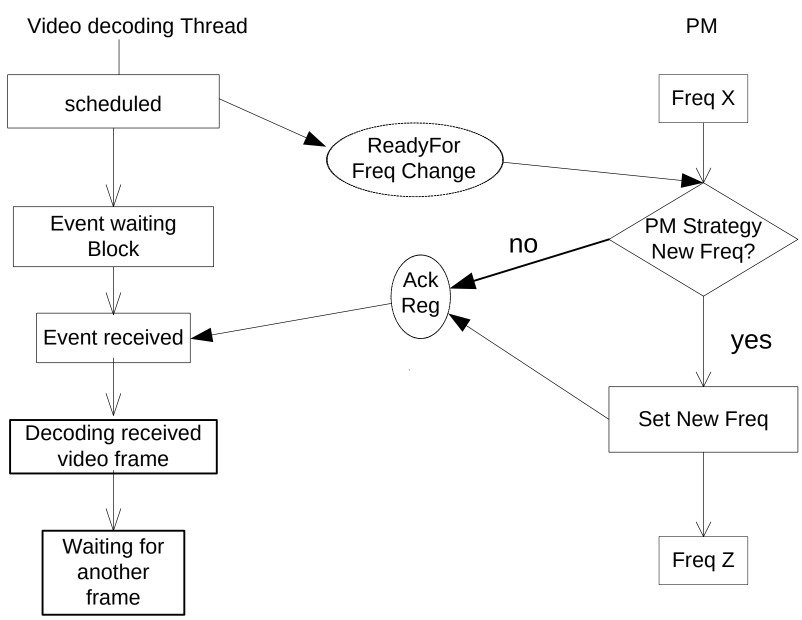


Figure 4.8 Request Frequency Change Process

Thread can use ChangeFrequencyBlock function to prevent PM from changing frequency. Note that the thread should use this function only when necessary. It must ensure to call ChangeFrequencyBlockRelease as soon as possible to unblock PM from changing frequency. Sometime video encoding thread may need these functions. It is safe to set 624MHz to ensure that there is enough performance for the entire system and PM is blocked from switching operation points when the thread is active. SetminimumOP is used to set a minimum operating point. PM cannot use an operating point below this minimum operation point. It is required to call SetMinumumOP_Release as soon as possible. Here the minimumOP refers to the minimum frequency of AP. For example, 108MHz is set to minimOP, which means PM cannot set frequency of AP lower than 108MHz.

4.2.3 Events for PM Strategy

The following events can trigger PM to make power management decision on switching operating points. These events come from several sources.

(a) Battery Monitoring Thread. This thread gets battery level from Operating System. Now the PM compares the read value with pre-setting threshold to decide which video size is suitable for video processing. In our simulation, PM switches to lower resolution operating points for both Video capture and playback when battery level reaches 50%.

(b) Profiler Module. As explained in sub-section 4.1.1, this thread calculates the AP utilization and monitors the memory and bus traffic. At the end of each sampling window, the statistic is delivered to PM. The value at 80% is used as the threshold value. If the CPU utilization reaches 80% at current operating point, PM starts to switch to operating points with higher frequency of AP. The sampling window $T_{idle\_sampling}$ is dynamically adjustable. For audio encoding/decoding thread, we set it to 300milisecond. When Video encoding/decoding thread starts, it is set to 1 second.

(c) Module of Real-time wireless video transfer application. After PM receives ready for operating point change message, PM evaluates if it is worthwhile to transit to a new operating point. If there is benefit for power consumption, PM starts to change frequency of AP, otherwise, system keeps running at current operating point.

The frequency and voltage change module is an important part of PM. PM uses this module to specify the target value of voltage and frequency of corresponding components. There are two power trails named VCC_Core and VCC_SRAM, which provide power to AP and Static random access memory. When PM changes Operating point, these two voltages need to be modified. Function Set_Voltage_OP was developed for setting voltage. A semaphone variable is designed to prevent multiple setting of voltage. Semaphone is an abstract data type that provides a simple but useful abstraction for controlling access by multiple processes to a common resource. After waiting on the semaphone, the function attempts to get the current VCC_SRAM and stores it in a variable Pre_VCC_SRAM. If getting current value of VCC_SRAM fails, the function releases the semaphone and returns an error code. But if it succeeds, the function proceeds to set the new value to VCC_SRAM. If setting new VCC_SRAM fails, semaphone is released and an error code is returned. But if it succeeds, the program proceeds to get current voltage of VCC_Core and saves it in variable Pre_VCC_Core. Now, the code attempts to set the new VCC_Core value. If the attempt to set the new VCC_Core fails, the previous VCC_SRAM voltage is restored to value in the Pre_VCC_SRAM. The semaphone is released and an error code is returned again. But if the attempt to set the VCC_Core succeeds, the semaphone is released and a success code is returned. For the frequency change, similar process is followed to modify bits of AP’s core clock configuration register (CCCR). Note that when changing frequency of AP from high to low, it is necessary to change the frequency before voltage is changed. When changing frequency to higher value, voltage needs to be changed before frequency is modified.

4.2.3 Simulation Result

First, an audio playback application is developed on a development board to demonstrate the effectiveness of PM. The development board simulates a cellular and handheld device. In order to get more accurate power consumption data, a tool named PowerME is used for sampling energy consumption for main hardware components. Using PowerME, it can be determined what fraction of the total energy consumed during a certain time period is due to specific hardware component. By providing fine-grained feedback, the PowerME helps expose system components most responsible for energy consumption. PowerME is from National Instrument Corp and uses statistical sampling to profile the energy usage of a hardware board. There are 12 sampling channels which are expandable and depend on how many components are needed to be sampled at the same time. Each channel samples the current drawn by the profiling board through its external power input. The input voltage on the component is sampled as well.

The application plays audio file in WMA format and stays in the looping mode. The Looping mode means the player plays the audio file from the beginning again when it reaches to the end of file. The audio sample used in demo is stereo and sampled at 44.1KHz. The bitrate of the audio file is 160Kbps and the duration is about 90 seconds. The PM strategy is implemented as described in section 4.2. But PM only responds to audio playback workload in this application. There are three sets of measurements, where the frequency of application processor is set to 208MHz, 416MHz and 624MHz, respectively when the system is in run mode. However, there are two options for operating point when system is in idle mode. One is 13MHz idle mode and the other is

104MHz idle mode. The difference between 13MHz idle mode and 104MHz idle mode is that the frequency of AP is set to 13MHz or 104MHz when system enters idle. We measure the current drawn from the battery for both options. The result is shown in Table 4. 3. As we can see, the current value improves more than 50% for all three running frequencies when 13MHz is chosen as idle operating point. It means the power consumption has been reduced more than 50% as power is the product of current and voltage. Here the voltage is a constant value. Let us assume a 1200mA battery is used. By taking 416MHz Run setting as an example, the current value of 13M idle and 104MHz idle are 54.79mA and 116.50mA, respectively. It means almost 21.9 music playback hours for 13MHz idle and 10.3 hours for 104MHz idle. The battery life is almost doubled for music playback usage. If PM is not used and frequency of AP does not change in the idle mode, the system stays at 416MHz when system enters idle. The power consumption is even worse than 104Mhz idle mode. The battery can only last at most 4 hours for music playback.

Table 4. 3 Current Measurements for Audio Playback with Different Idle Operating Points

	208MHz Run		416MHz Run		624MHz Run	
	13MHz idle	104MHz idle	13Mhz idle	104MHz idle	13MHz Idle	104MHz idle
WMA	55.81mA	112.14mA	54.79mA	116.50mA	61.85mA	125mA

Next, a Video playback application is developed to demonstrate how PM affects power consumption when Video file in WMV format is played. The player is also set to the looping mode. PM only responds to video decoding workload this time. The video‘s resolution is 320*240 and is played at 24 frame per second with bitrate of 384kbps. The duration of video is about 60 seconds. The frequency of application processor is set to 208MHz, 416MHz and 624MHz, respectively when the system is in run mode and we measure the current drawn from the battery again. Table 4. 4 shows the results of current measurement for 13MHz idle and 104MHz idle. Compared with 104MHz idle, when 13MHz is chosen as idle operating point for video playback, the current value improves 21%, 30.7% and 26.7% for AP running frequency at 208MHz, 416MHz and 624MHz, respectively. From the power saving perspective, the percentage of power improvement of video playback is less than that of audio playback. The reason is that video playback requires more computation power than audio playback. It means the application processor spends less time in idle mode when decoding video frame. The longer the system stays In idle mode, the more power is saved.

Table 4. 4 Current Measurements for Video Playback with Different Idle Operating Points

	208MHz Run		416MHz Run		624MHz Run	
	13MHz idle	104MHz idle	13MHz idle	104MHz idle	13MHz Idle	104MHz idle
WMV	112.15mA	141.18mA	105.26mA	151.90mA	139.54mA	190.48mA

Finally, a simulation with all modules of real-time wireless video transfer application is implemented with integrated PM. The simulation conducts the video capturing and H.264 and GSM-AMR encoding/decoding. It supports QCIF, QVGA and CIF. The video encoding runs at a bit rate from 64kbps to 384kbps. Aside from that, the simulation provides a Picture-in-Picture preview window feature, which is about 1/12 of the size of the display sitting on the top left corner of LCD screen, and displays the image captured by the local camera.

Power consumption of the system is measured for both PM enabled and PM disabled conditions. When doing PM disabled simulation, the frequency of AP is set to the value of 624MHz. This simulation has all modules of real-time wireless video transfer application and it is necessary to run the system at the maximum performance. The power data is sampled about 20 times per second. The results are shown in Figure 4.9. The figure shows PM enabled simulation has less power consumption for the most of sampling time compared to PM disabled simulation. The average of sampled power data is about 254.3mW and 456.65mW for PM enabled and PM disabled simulations respectively. It represents about 44.3% power consumption improvement. The battery life can almost be doubled by using PM. It is also noted that the power consumption is approximately same for both PM enabled and disable simulations from 0.2s to 0.3s. Application processor must have heavy workload during that time slot. PM enabled simulation sets the frequency of application processor to 624MHz to meet such requirements for computation power. At 624MHz, the application processor delivers maximum performance that system can provide.

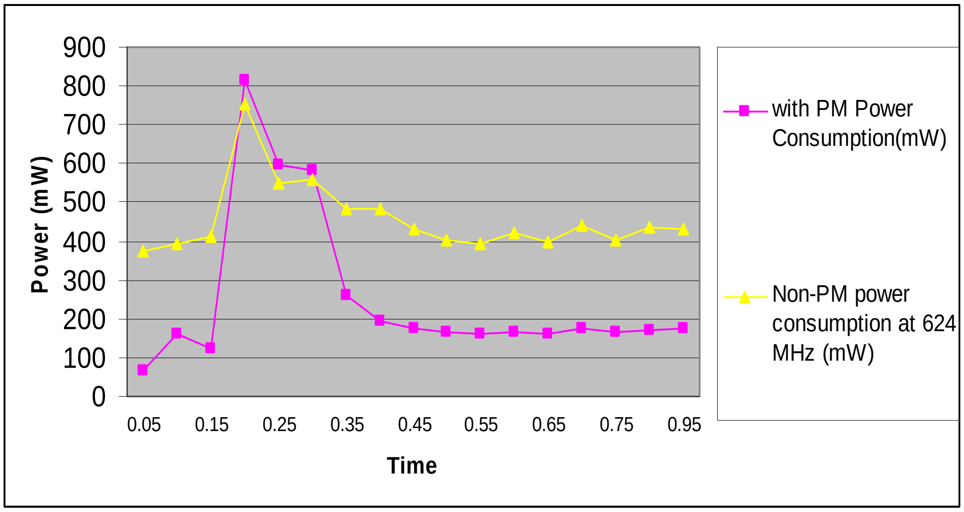


Figure 4.9 Power Consumption with PM Enabled and Disabled

4.2.3 Conclusion

The implementation of PM is has been discussed and analyzed in this chapter. Each function of PM and how PM works with every module of real-time wireless video transfer application is described in detail. The simulation results show that PM optimizes system power consumption and extends battery life significantly. In next chapter, the power consumption is optimized from network perspective.

Chapter 5

Power Conservative Integrated Multi-hop Real-time Wireless Video Transfer Network

In order to improve power efficiency further, optimization should not be considered by utilizing the hardware advancement only. Significant additional power can be saved by incorporating low-power strategies into the design of communication networks and corresponding data communication protocols. In this chapter, a method for system power performance improvement has been proposed by leveraging new network architectures. By taking into consideration both computation and communication costs, we have made a balance to achieve overall power conservation improvement for real-time wireless video transfer applications.

Path loss is a big factor which affects system power utilization in wireless communications. It is the attenuation undergone by an electromagnetic wave in transit from transmitter to receiver. Path loss may be due to many effects such as free-space loss, refraction, diffraction, reflection, aperture-medium coupling loss, and absorption. Path loss is affected by factors such as terrain contours, different environments like urban or rural, vegetation and foliage, propagation medium (dry or moist air), the distance between transmitter and receiver, the height and location of their antennas, etc. An optimized network topology consumes less power if the distance between the transmitter and receiver can be reduced. Further, better efficiency in power utilization can be achieved with low complexity in the routing and load balancing algorithms used by wireless networks. In the following, we present an optimum hierarchical routing strategy with low complexity which employs a sophisticated layer-scheduling algorithm based on the load-balancing objective. The simulation results show that the developed layer scheduling algorithm achieves indeed the perfect load balancing for networks with various traffic properties as well as low computation cost for the system.

5.1 Introduction

In the wireless network arena, the canonical model of wireless networking is the cellular network, which has been the most common model for providing Internet access for Cellular and Handheld devices. In the cellular networks, land based bridges, known as base stations, are used to provide connectivity. A cellular or handheld device within this network directly communicates with the base station whose coverage area (i.e. cell) includes the location of this device. A key reason behind the adoption of the cellular model for wireless data communications is its ability to simply reuse existing voice network infrastructure. However, the existing cellular networks are unable to scale to high data rates and to cope with the accelerated growth in wireless user devices. It has prompted researchers and the communication industry to explore alternative network solutions. In this context, *ad-hoc or multi-hop networks* have gained attention by virtue of their ability to operate with a peer to peer network model. The transmission range of each wireless node is just large enough for the network to be connected. In order to transmit a message beyond the range of a single node, a node must rely on one or more intermediate nodes to relay the messages to its final destination. In this case, the power consumed by a transmitter is much lower compared to a traditional wireless mode. Spatial reuse is another benefit which allows network capacity to be increased enormously due to small transmission range. On the other hand, the ad-hoc networks are vulnerable to frequent network partitions and route failures that essentially prohibit them from being widely used in many critical and commercial applications. Therefore, a trend toward integrating ad hoc and cellular networks has emerged. It is becoming highly desirable for ubiquitous wireless communication with deeper coverage, lower power, and higher capacity. The integrated network approach offers the existing cellular system with multi-hop access thereby greatly expanding its coverage, significantly increasing its capacity of providing packet data services, and drastically lowering power consumption. The Integrated Multi-hop Cellular Data Network (IMCDN) has been designed as a novel architecture to realize such an integrated network approach [42]. Based on IMCDN, we extend and design new usage model for real-time video transfer applications. Figure 5. 1 conceptually illustrates network architecture of new usage model and it is named as RVTNA. In this network architecture, the multi-hop access network consists of Cellular and Handheld devices, which act as *routing nodes* (RN). They are strategically positioned to achieve efficient delivery of data packets from other Cellular and Handheld devices to any available base station (BS) regardless of their physical locations.

For this multi-hop access network, the MSC is responsible for all the decision and control aspects of major link- and network-layer functions including controlling self-organizing cycle, maintaining routing topology, and coordinating medium access, at the same time the BSs act as agents carrying out these functions.

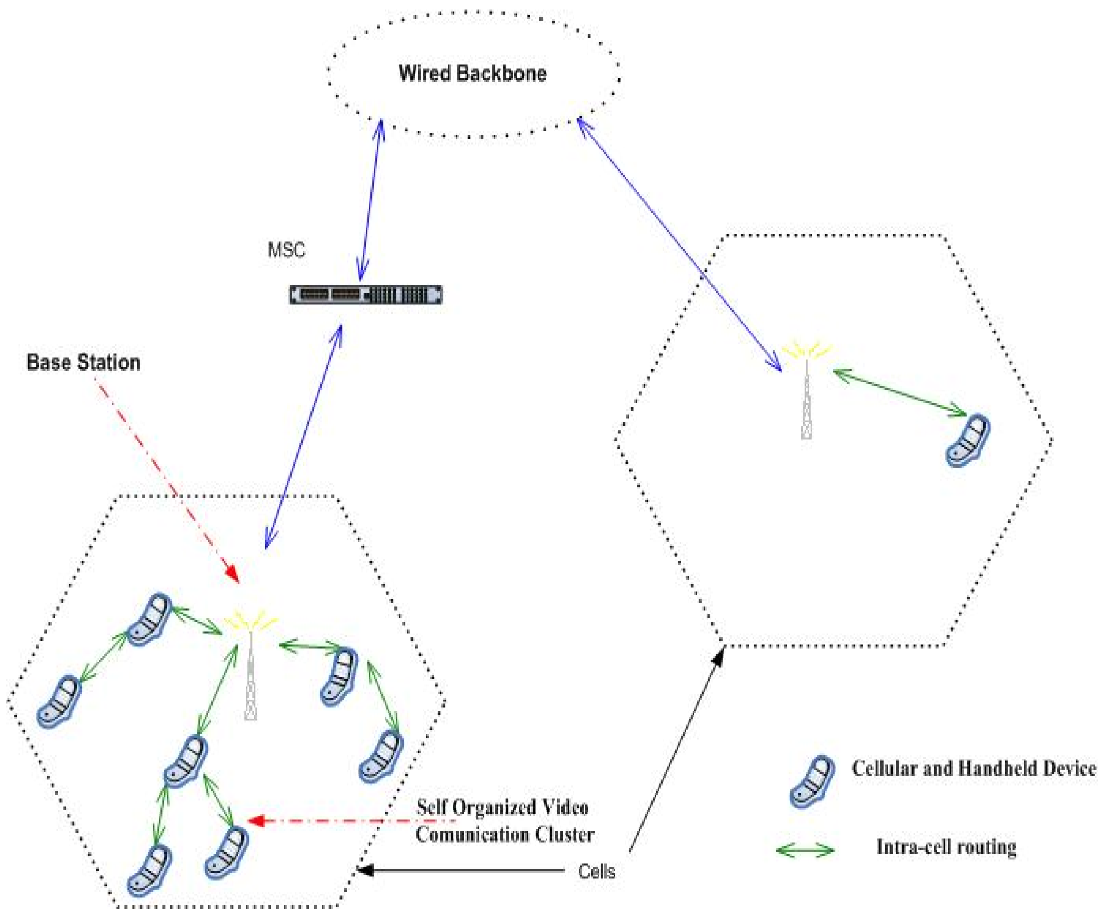


Figure 5. 1Real-time Video Transfer Network Architecture (RVTNA)

The authors of [42] have introduced a group based TDMA medium access control (MAC) protocol for the IMCDN to ensure that the frequency resources are optimally used by the multi-hop access network. Assuming the perfect load balancing among cells through the dynamic routing of the unevenly distributed Cellular and Handheld device's data traffic, it has been shown that the IMCDN system capacity is many times larger than that of a conventional one-hop system with the designed MAC protocol.

We present a novel routing and signaling protocol that achieves in effect the perfect load-balancing among cells in the RVTNA. Even though there have been numerous routing protocols proposed for ad-hoc multi-hop networks [48], the need of a new routing protocol specific for the RVTNA arises from particular properties of the multi-hop access network formed by RNs: i) RNs are quasi-stationary nodes as parts of the network infrastructure, ii) the final destination for upstream data packets is always a BS, iii) the downstream data packets are always originated from a BS, and iv) the MSC can act as a central controller. In addition, the routing scheduling in the RVTNA involves special objectives, i.e., load balancing and power saving. At the same time, the computation cost is reduced significantly because of the efficiency of the scheduling algorithm and compact signaling protocols.

There have been reported several approaches to overlaying a multi-hop network on an existing cellular network. For example, the Multi-hop Cellular Network (MCN) presented uses mobiles to relay traffic to a BS as discussed by the authors of [43] . ICAR introduces routing nodes for mobiles to reach a BS as our RVTNA in [44]. Here, the analysis and architecture are connection based instead of packet-data based. The system SOPRANO presented in [45] also uses routing nodes to support multi-hop communication between mobiles and BSs, but it has focused on capacity related to CDMA. It is worthwhile to note that the presented load balancing algorithm and routing protocol in this chapter can mesh well with all these other architectures.

The rest of the chapter is organized as follows. In Section 5.2, the signaling protocol and the hierarchical routing technique has been discussed. Section 5.3 presents a distributed packet scheduling algorithms based on the load-balancing objective. Next, the performance of the proposed algorithm has been accessed through the simulation study in Section 5.4 and final conclusion has been drawn in Section 5.5.

5.2 Signaling Protocols and a Hierarchical Routing Strategy

RVTNA is a multi-hop access network, which is densely populated with a large number of stationary nodes throughout the service area of an MSC. The nodes are capable of self-organizing themselves to create a routing topology to support multi-hop data communications. Here the main focus has been in using rooted spanning trees as routing topology based on the distance vector technique [49]. Each rooted spanning tree is referred as a layer. While a BS in the RVTNA serves as a root node, all the RNs in the RVTNA are non-root nodes for any given layer. Thus the number of layers equals the number of BSs within the service area of the MSC. The concept of the layer breaks the cell boundary in the conventional cellular network and thus enables the multi-hop access network to provide a seamless access of a Cellular and Handheld device to any available BS in the service area. Within a spanning tree hierarchy of a layer, a *level-d* node has a depth *d* if it is *d* nodes away from the root. Each non-root node, regardless of its level, needs to maintain a simple *layer table* for all available layers in order to carry out its packet routing responsibilities. A layer table entry contains Layer ID, and accordingly its parent ID and its depth. Within the hierarchy of the spanning tree of the layer, all RNs situated in the subtree rooted at an RN are said to be *descendents* of the latter. On the other hand, the latter is said to be an *ancestor* of the formers. Figure 5. 2 illustrate an example of the descendant and ancestor relationship within the spanning tree hierarchy of the layer. For instance, *Nodes 5, 6, 7,* and *8* are *Node-3's descendents* and *Node-3* is their *ancestor*.

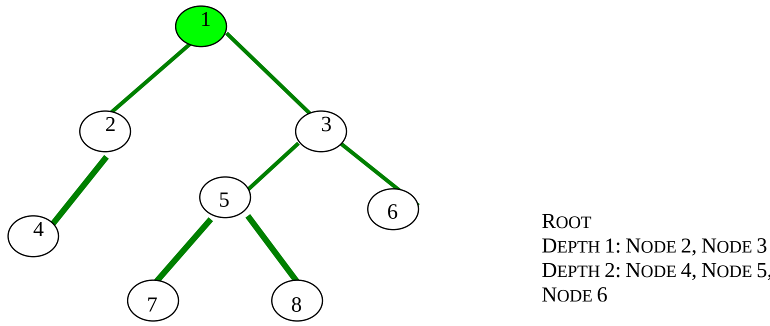


Figure 5. 2 An Example of the Descendent and Ancestor Relationship

Basically, the presented routing protocols associated with RVTNA are extension of that of the multiple-layer self-organizing network in [50]. However, a major deviation from the original routing protocol and architecture is that the multi-hop relaying over the layers is engaged in both upstream and downstream data packet transmissions within the RVTNA architecture.

5.2.1 Layer Construction and Maintenance

A layer is constructed and maintained based on the underlying physical network topology and used for both upstream and downstream packet routing. The RN additions to a layer are performed in a sequential manner starting from the root and a layer is updated as soon as a change in the network is detected for complete description of the Layer Construction process [50][54]. As a new node enters a network, it becomes a member of multiple spanning trees associated with the multiple-layer network. The Depth-1 nodes within a given Layer k, are the nodes within the range of the root of Layer k. The Depth-2 nodes within Layer k are nodes within the range of the Depth-1 nodes of Layer k, but outside of the range of the root of Layer k. Upon detecting a new RN, the existing RN updates its range through a three-way handshaking [49]. We define the range for *RN i* as the set of nodes to and from which *RN i* can communicate directly. As soon as *RN i* learns of its range, it finds an RN with the smallest depth to the root within each available layer. *RN i* selects this node to be its parent for that layer, sets its own depth within that layer to be one plus the depth of its parent, and records this information in its layer table as shown in Table 5. 1. *RN i* also keeps a range table for its neighboring nodes as shown in Table 5. 2. It records the Node ID, deptth and layer ID of all neighbors of Node *i*. These two sepecially designed tables are key parameters for routing technique implemented in 5.2.3.

Table 5. 1 Routing table of Node *i*

k	The Layer ID
$D_i^{(k)}$	The depth of Node I in Layer k
$P_i^{(k)}$	The parent node in Layer K whose depth achieves $\min_{Node j \in R_i} D_i^{(k)}$ in Layer k

Table 5. 2 Range Table of Node *i*

J	Node ID of Node j, $j \in R_i$
K	The Layer ID
$D_i^{(k)}$	The depth of Node j in Layer k

Each RN is responsible for broadcasting a control packet periodically to all its neighbors to support the maintenance of the layers. Table 5. 3 illustrates the control packet format. In order not to participate in packet relaying for other RNs, an RN can announce itself to be a *leaf node* i.e., a node with no descendent in the layers for some duration if its load is higher than the threshold value. This can be achieved by setting the depth value to infinity embedded in the periodic control packet. The *RN i* receives control packets from other RNs in its Range. The R_i reads and records the depth value of the sender included in the control packet and compares it with its stored value. Only when two values are different, it computes new minimum depth to the root BS incorporating the new depth value from the sender. If the new minimum depth is larger than its own depth, it computes a new parent within the layer. An example of a 2-layer network with Layer 1 rooted at Node 1 and Layer 6 rooted at Node 6 is shown in Table 5. 4, Table 5. 5 and Figure 5. 3.

Table 5. 3 Control Packet Format

Packet Type	Source ID	Layer ID	Depth

Table 5. 4 Routing Table of Node 4 in Figure 5.3

k^*	$D_i^{(k)}$	$P_i^{(k)}$
1	2	2
6	1	6

Table 5. 5 Range Table of Node 4 in Figure 5.3 where $R_4 = \{2,3,5,6\}$

J	K	$D_i^{(k)}$
2	1	1
2	6	2
3	1	2
3	6	2
5	1	2
5	6	2
6	1	3
6	6	0

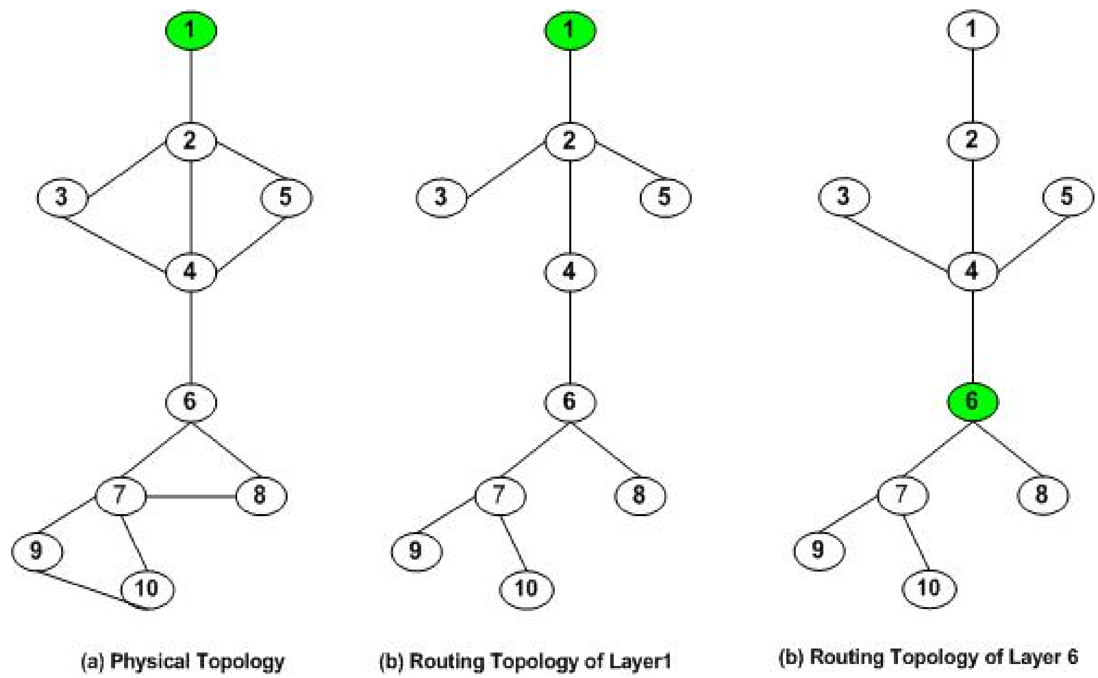


Figure 5. 3 An example of a 2-layer network with Layer 1 rooted at Node 1 and Layer 6 rooted at Node 6

5.2.2 Signaling for the Cellular and Handheld Device's Mobility Management

It is noted that one of the objectives of the RVTNA is that RNs and the added functions to the existing BSs are required to be simple enough to build a low-power and low-cost access network. In order to achieve this end, all the intelligence from RNs and the BSs are pushed to the MSC. The MSC maintains routing topology information i.e., the physical topology and the spanning trees of layers of the multiple access networks. It also performs the Cellular and Handheld device's mobility management.

For the Cellular and Handheld device's location management, the Cellular and Handheld device updates the MSC as to the set of RNs from which it can receive a signal reliably. Specifically, when a Cellular and Handheld device is turned on and is not yet engaged in data communication, it first scans control channels for nearby RNs in order to determine its environment. The control channels are used by RNs to broadcast their presence. The Cellular and Handheld device records the RN(s) from which it receives the control packets directly and informs the MSC of this information. The RN directly communicating with a Cellular and Handheld device at the last hop of the layer is referred to as a *serving RN* in this dissertation. A serving RN can be any of RNs within the transmission range of a Cellular and Handheld device.

The MSC is also responsible to inform RNs of network status via direct broadcast from a BS. Since the transmission range of a BS i.e., root is basically limited to the coverage area of a base station, an RN can learn the entire network status from the BS of the cell it is located in.

5.2.3 Routing Technique

Leveraging the hierarchical spanning tree topology of layers and the characteristics of the traffic direction in the RVTNA, an efficient routing technique is presented in this section. In order to communicate upstream, data packets from the source Cellular and Handheld device are transmitted to a nearby RN and are then relayed to the BS as the final destinations for upstream data packets are always BSs. The upstream data packet relay to a BS can be achieved in an extremely simple way by utilizing a layer table. Upon receipt of a data packet from a Cellular and Handheld device, the RN chooses a layer according to the layer scheduling algorithm described in Section 5.3 and transmits the data packet to its parent with respect to the spanning tree of that layer. By checking its routing table and range table as defined in Section 5.2.1, the RN can immediately locate its parent ID of that layer and fill the header of data packet for routing. Table 5. 6 illustrate the data packet format used in the RVTNA. In the case of upstream packet transmission, the serving RN ID field is set to the ID of the serving RN that receives the data packet directly from the Cellular and Handheld device. The Layer ID field is set to the root BS ID of the selected layer. The Serving RN ID is unchanged during the packet relay. The source is set to the ID of relay RN which forwards the data packet and the destination to the ID of destination Cellular and Handheld device. For example, if node 7 in Figure 5. 1 wants to send data packets to node 4, the data packet with routing header are going to be as shown in Table 5. 7. It means the content is decided by the application, where Packet Type can be upstream or downstream.

Table 5. 6 Data Packet Format

Packet Type *	Serving RN ID	Layer ID	Source	Dest	Data *

Table 5. 7 An Example of Upstream Data Packet with Routing Header

Packet Type	Serving RN ID	Layer ID	Source	Dest	Data
upstream	5	1	5	4	*

On the downstream, *the MSC selects a layer* according to a BS to relay data packets to the destination Cellular and Handheld device which is a video conferencing receiver in this case. It is done according to the layer scheduling algorithm discussed in Section 5.3. Following the selected layer in reverse order, the data packet is passed down from the root BS to the serving RN of the destination Cellular and Handheld device. As MSC learns the set of serving RN candidates for the corresponding destination Cellular and Handheld device through the signaling protocol described in Section 5.2.2, MSC is able to select the serving RN for the destination Cellular and Handheld device. Then it creates the downstream packet and writes the serving RN field as well as Layer ID field according to its selections. The values in these fields will not be changed by the intermediate RNs following the selected layer.

The downstream data packet is sent by the MSC as described earlier. The serving RN ID field is set to the ID of the serving RN that delivers data packet directly to the destination Cellular and Handheld device. The Layer ID field is set to the root BS ID of the selected layer. The source field is set to the intermediate RN which relays the data packet and the destination field to the broadcast address. The intermediate destination cannot be a specific address for the downstream packet because RNs do not possess the next hop information for each serving RN in order to reduce the routing information. Unlike other routing protocols for pure ad-hoc networks, this intermediate destination is determined by receiving RNs instead of transmitting RNs by utilizing layers. Specifically, in order to pass down the data packets following the chosen layer, every receiving RN first decides whether to forward or discard the packet. The packet is forwarded only if it was sent from the parent node and the destination RN is one of its descendents in the given layer. For instance, as shown in Figure 5. 1, *Nodes 2* and *3* receive the data packet shown in Table 5.8 and even though *Node 1* is the parent of both *Nodes 2* and *3*. *Node 2* discards the packet and only *Node 3* forwards it. It is due to the fact that the serving node, *Node 7*, is one of its descendents.

Table 5. 8 An Example of Data Packet

Packet Type	Serving RN ID	Layer ID	Source	Dest	Data
downstream	5	1	1	7	*

Here, the RN recognizes that the packet is forwarded by the parent node by matching the source field with the parent ID in the layer table. For descendent checking, every RN is required to maintain *the descendent list* with respect to each available layer for the downstream routing. It is noted that RN maintains not only the list of all the descendents but also the list of the *active* descendents in order to reduce the routing overheads. An RN is said to be *active* if it transmits or receives data within the last predefined time period. An active descendent RN can be added to the descendent list of its ancestors through the *learning procedure* resembling the *backward learning of the transparent bridges [49]*. Unlike the operation of the transparent bridges, the protocol proposed here avoids the initial flooding stage. Instead, capitalizing on the cellular infrastructure, the BS always transmits the addressed-broadcast to the serving RN for initial connection set-up with the destination Cellular and Handheld device as directed by the MSC. It is also enforces the serving RN to transmit a pilot data packet without any data payload through all the available layers. The intermediate RNs following every available layer read *the serving RN field* whenever they forward a pilot data packet, and then record the RN ID as its active descendent. Note that the intermediate RNs only record the serving RN information instead of all RNs along the routing path so that the size of the descendent list maintained by each RN can be minimized. Now the serving RN becomes active along the hierarchical routing path of the available layers and thus is known to its ancestors within the layers since the pilot packet from the serving RN has been relayed. Upon receiving the pilot packet, the MSC starts to transmit downstream data packets to the destination Cellular and Handheld device via serving RN.

In summary, each RN is required to maintain a layer table for the available layers of spanning trees and its descendent list as shown in Figure 5. 4 to perform their relaying responsibility. Whenever an RN receives a downstream data packet, it reads the serving RN field and updates the *timestamp* of the corresponding RN. Then, each RN periodically deletes any descendents in the list if the timestamp value is older than the threshold time instance. In this way, RNs keep only active descendents in the list.

Figure 5. 4 The Layer Table and the Descendent List

Layer ID	Parent ID	Depth

(a) The Layer Table

Layer ID	Descendent ID	Timestamp

(b) The Descendent List

5.3 A Distributed Layer Scheduling Algorithm with the Load Balancing Objective

It is assumed that the frequencies available for multi-hop access networks are those channels of the existing cellular system, that are either unused by the cellular voice and/or data service or are specifically reserved for the multi-hop packet data service. Hence, the set of available frequencies varies from cell to cell i.e., layer to layer and may vary with time also. Without the load balancing technique of the RVTNA, the capacity and the service performance of the conventional cellular system may largely vary depending on traffic load distribution and also channel availability. Therefore, in this section, the load balancing among layers is considered in an attempt to optimize the network performance, that is, the possibility of the congestion is minimized and the network capacity is maximized as shown in [42]. The layer scheduling with the load balancing objective is designed based on the available capacity of each layer or each cell and is incorporated with the hierarchical routing protocol presented in Section 5.2.3.

There is only few research papers focused on the load balanced routing in wireless networks [51][53]. These papers mostly discuss how to configure routing path which balance the load among intermediate wireless nodes. The subject for load balancing in RVTNA is quite different due to its unique environment. Specifically, the capacity of a single layer, due to hierarchical routing, is bounded by the capacity of its last hop, i.e., between the level-1 nodes (nodes with unit depth) and the BS. Consequently, the focus needs to be not on the intermediate nodes but on the bottleneck nodes, i.e., BSs. Therefore, in this research, the focus is on the load balancing among layers in terms of the available capacity of the last hop, that is, available channels to access BSs.

The BSs in the RVTNA advertises the network status information within each period. This information is used by RNs for making layer scheduling decision during the following period. Ideally, the length of the period should be determined based on traffic characteristics and channel data rate. Network status information broadcast by each BS includes not only the available capacity of its own layer but also those of other layers in the service area of the MSC. An update timer is maintained at the MSC to periodically initiate a load information broadcast cycle. Specifically, the MSC periodically collects the load status of each layer from the corresponding BS and then informs all BSs of the load status of all the available layers in the system. The load status of *Layer-k* in this work is the available capacity in *Cell-k* in terms of the number of channels to access the BS. Each channel is assumed to have the same capacity of R_{ch} bps. This is a reasonable assumption because a transmission path between a BS and level-1 RNs (fixed nodes) ought to be short and thus the data rate per channel does not vary much when a new upstream data packet arrives at an RN, If the RN receives the packet directly from the source Cellular and Handheld device, then it decides the layer to forward the packet, based on the layer scheduling algorithm. It then writes the selection in the Layer ID field of the data packet whose format is shown in Table 5. 6 in Section 5.2.3. If the data packet comes from its child RN, the RN reads the Layer ID field and forwards the packet using that layer.

Similarly, when a downstream data packet arrives at the MSC, the MSC simply selects the layer to forward the packet, based on the layer scheduling algorithm. The upstream and downstream packets are scheduled to all BSs proportional to their capacity by the serving RN and the MSC, respectively. In principle, if the packet size is constant and the available capacity of all the layers are same, then a round robin algorithm may be adequate for load balancing the layers at each packet arrival. In practice, this is hardly the case. Therefore, a sophisticated algorithm is proposed that is able to handle variable length packets in the cellular system with the unbalanced available capacity as well as the unbalanced traffic distribution per cell. The scheduling algorithm is described only in view of the RN because the scheduling method for the downstream executed by the MSC is exactly same with the one of each serving RN. In order to describe the details of the scheduling algorithm, the following notations and definitions are selected.

C_i : the set of available channels in *Layer-i* in the RVTNA where $1 \le i \le L$ and L is the number of layers i.e. the number of BSs in the system

A_n^i : the total traffic load in bytes forwarded to *Layer-i* by *RN n* where $1 \le i \le L, 1 \le n \le N$ and N is the number of RNs in the system

$P_n^{(t)}$: the packet size in bytes that *RN n* receives at the time index t provided that the packet size is variable. The time index t represents the t^{th} packet arrival.

At the moment each RN receives a data packet from the source Cellular and Handheld device and makes the selection of a layer to forward, it strives to minimize the distribution error. Specifically, the RN individually attempts to minimize the difference between the average channel utilization of the whole system and that of each layer. Consequently, the amount of traffic globally received by a BS is proportional to its capacity. When an RN selects *Layer-i* to forward the packet at the t^{th} arrival, the distribution error is defined as:

$$E_i^{(t)} = (A_{avg}^{(t)} - \frac{A_n^i + P_n^{(t)}}{C_i})^2 + \sum_{j=1 \quad for\ j \neq i}^{L} (A_{avg}^{(t)} - \frac{A_n^j}{C_j})^2 \quad \textbf{(5.1)}$$

where $A_{avg}^{(t)}$ denotes the average load per channel in the system given by the *RN n* until the time index t and it is defined as:

$$A_{avg}^{(t)} = \frac{\sum_{k=1}^{t} A_n^{(k)}}{\sum_{i=1}^{L} C_i} \quad \textbf{(5.2)}$$

In Equation, the first term, $(A_{avg}^{(t)} - \frac{A_n^i + P_n^{(t)}}{C_i})^2$, represents the error contributed by the selected *Layer-i* and the second term $\sum_{j=1 \quad for\ j \neq i}^{L} (A_{avg}^{(t)} - \frac{A_n^j}{C_j})^2$ is the error by other layers which are not selected.

Then, the optimization problem for the RN to choose a Layer for data packet forwarding is to find *Layer-s* that achieves

$$E_s^{(t)} = \min_{1 \le i \le L} [\, E_i^{(t)} \,] \quad \textbf{(5.3)}$$

Since the RN computes the distribution errors for *L* cases when selecting a layer for the *L-layer network* and compare these *L* error values, the computational complexity of the proposed algorithm is just O(L).

5.4 Simulation Study

A constructed a simulation model using MATLAB has been conducted. The main objective of the simulation study is to gain insight into the performance of the proposed layer scheduling algorithm. We consider a seven-cell system as shown in Figure 5. 5. The numbers of channels available in each layer i.e. each BS are set to 10, 20, 30, 40, 50, 60, 70 for *cells 1, 2, 3, 4, 5, 6*, and *7*, respectively. Here only the upstream traffic distribution pattern is simulated because the scheduling method for both upstream and downstream traffic is similar while only the entity executing the algorithm is different.

In the simulation, an RN located in *Cell-1*. The cell at the center distributes its upstream data traffic proportional to the capacity of each layer following the presented layer scheduling algorithm described in Section 5.3. A traffic generator has been modeled to mimic the traffic generated by MDTs served by an RN. Without loss of generality, each MDT served by the RN independently generates packets by a Poisson packet arrival process. It is superposed to form a Poisson arrival process to the RN based on the superposition property of the Poisson process [47]. Therefore, the packet inter-arrival time to the RN used in the simulation study accounts for the packets generated by all the Cellular and Handheld devices served by the RN.

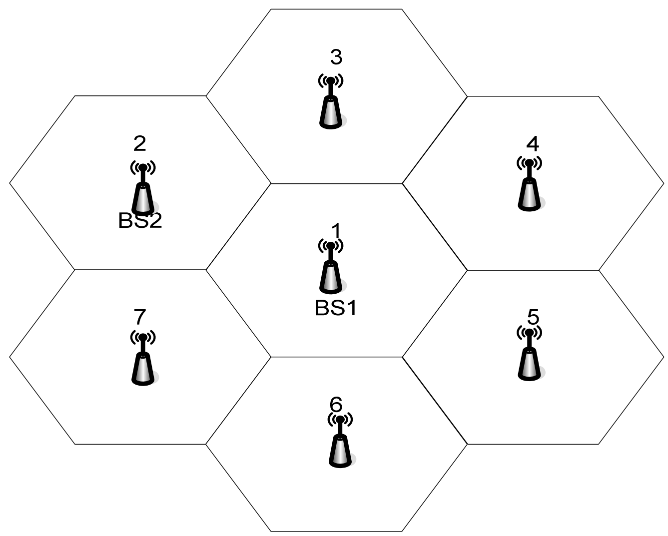


Figure 5. 5 A Seven-cell System

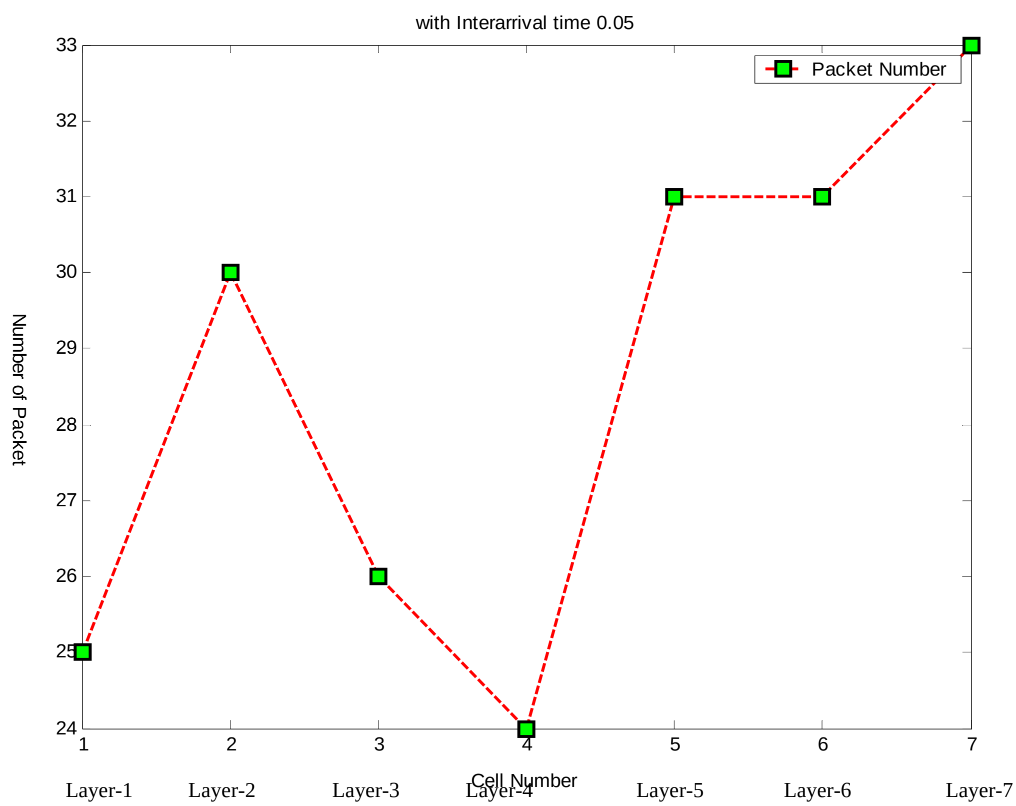
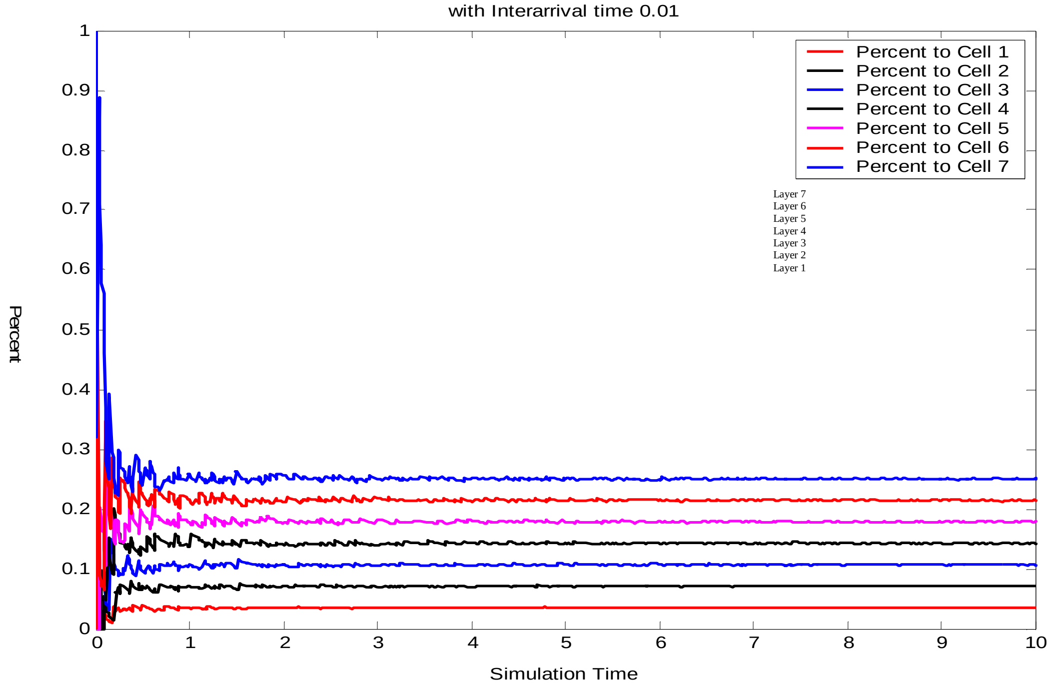


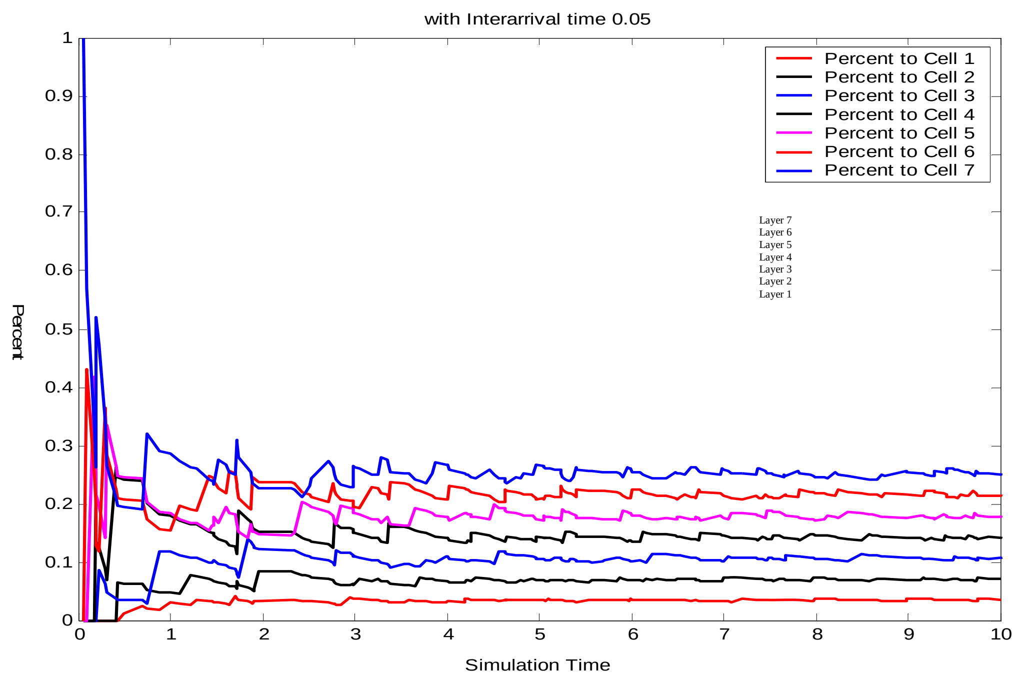
Fig. 5.6

Figure 5. 6 The number of packets allocated to each layer with the 0.05s inter-arrival times

First of all, it is analyzed how the traffic load affects the settling time. The network traffic load is varied by varying the mean inter-arrival time of data packets as 0.01sec, 0.02sec, 0.05sec, and 0.1sec. To be practical, the size of a data packet from the traffic generator was set to be exponentially distributed with a mean of 1024 bytes. As shown in Figure 5. 6 for the case of 0.05sec inter-arrival time, the number of packets distributed to each layer is arbitrary because the packet length is not constant. On the other hand, Figure 5. 7 illustrate the ratio of traffic allocated to each layer while varying packet inter-arrival times. Obviously, all cases reach the steady state while the settling time increases as the traffic load decreases i.e., the mean inter-arrival time increases. As noted in Section 5.3, the load information broadcast cycle can be ideally determined in relation with the speed of the packet arrival process. Therefore, the slow packet arrival process may require the longer broadcast period and thus the relatively prolonged settling time is still acceptable.



(a) Inter-arrival Time 0.01sec



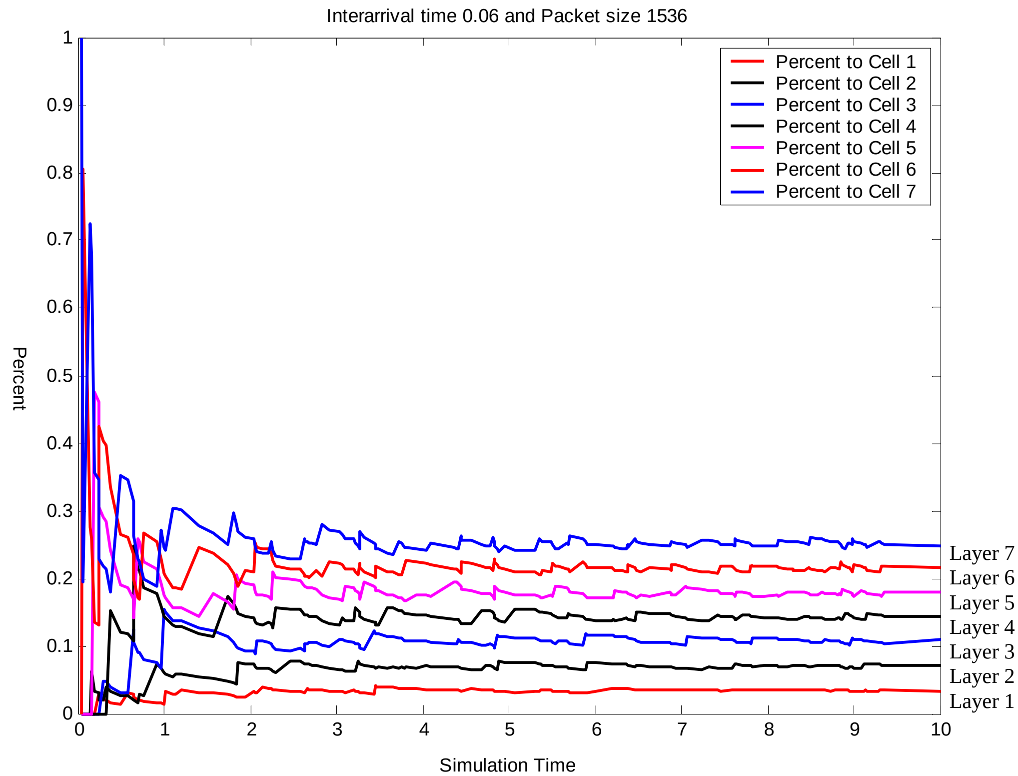
(b) Inter-arrival Time 0.05sec

Figure 5. 7 The ratio of traffic assigned to each cell with the different inter-arrival times

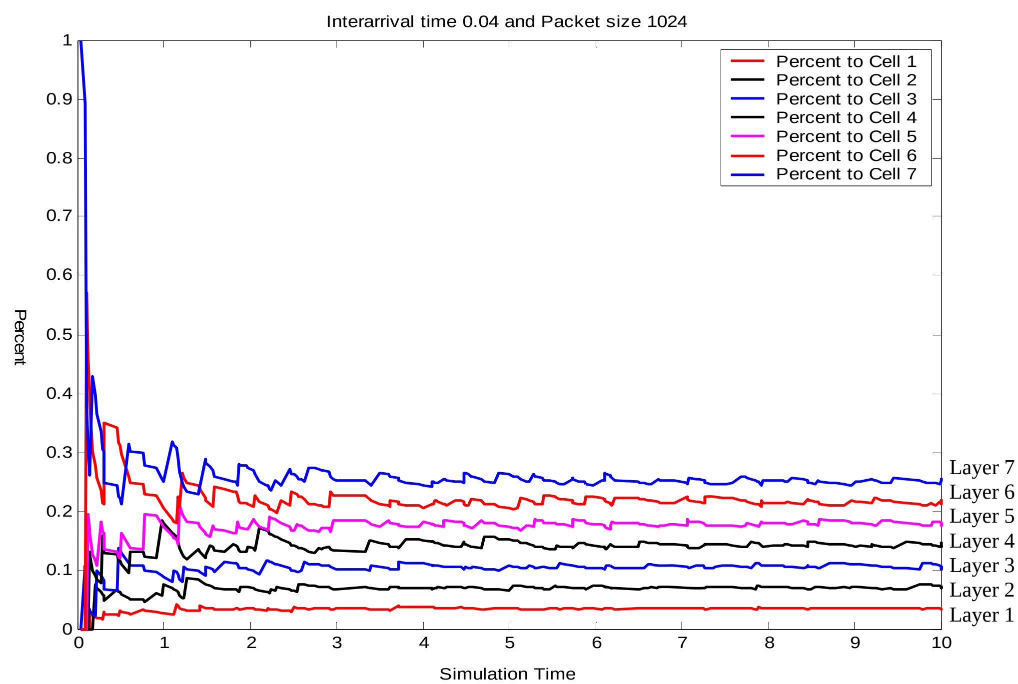
Next, the performance of the scheduling algorithm is observed depending on the average packet size. In order to maintain the average offered load to the RN to be at the same level, i.e., 200 Kbps, and thus to observe the impact purely due to packet size, both inter-arrival time and average packet size have to be varied as described in Table 5. 9. As shown in Figure 5. 8, the case with the smallest average packet size (256 bytes) yields the shortest settling time at about 0.5 sec and the most stable response in the steady state. On the contrary, the case with the largest average packet size displays the longest settling time around 5.5 sec.

Table 5. 9 Inter-arrival Times and Packet Lengths

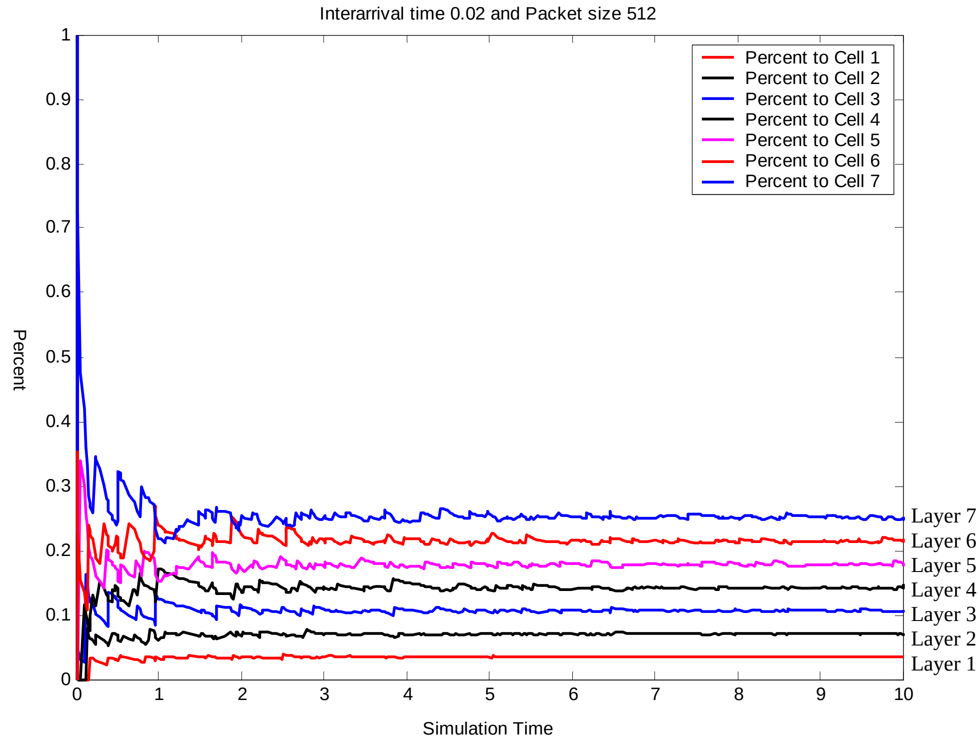
Packet Inter-Arrival (sec)	0.06	0.04	0.02	0.01
Avg Packet Length (bytes)	1536	1024	512	256



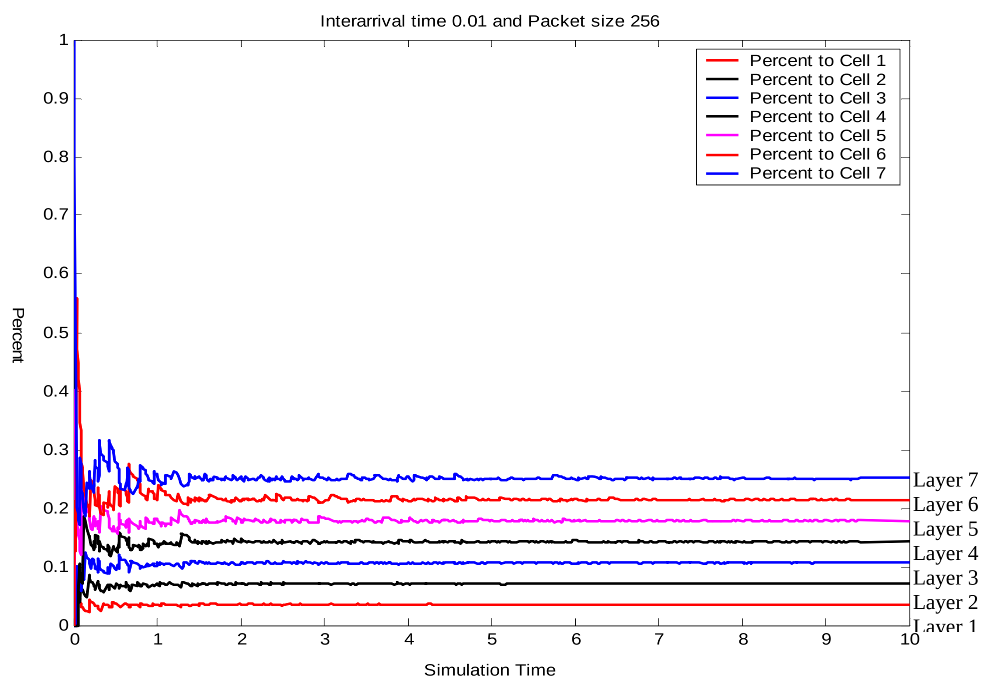
(a) Inter-arrival Time 0.06s and Packet Size 1536 bytes



(b) Inter-arrival Ttime 0.04s and Packet Size 1024 bytes



(c) Inter-arrival Time 0.02s and Packet Size 512 bytes



(d) Inter-arrival Time 0.01s and Packet Size 256 bytes

Figure 5. 8 The ratio of traffic assigned to each cell with different Inter- arrival times and packet lengths

So far, in the simulation study, the average traffic load during a load information broadcast period is assumed to be unchanged. Now the performance of the algorithm is analyzed in more practical environment where the arbitrary load change occurs in the middle of a broadcast period. That is, starting from 0.05s, the mean inter-arrival times is changed to 0.01s and 0.1s every five seconds. The time instances at which the packet inter-arrival times change are marked with circles in Figure 5. 9. The simulation results yield that the disturbance caused by the offered traffic load change is almost unnoticeable and rebalancing is obtained instantly, which significantly improves the bandwidth blocking rate.

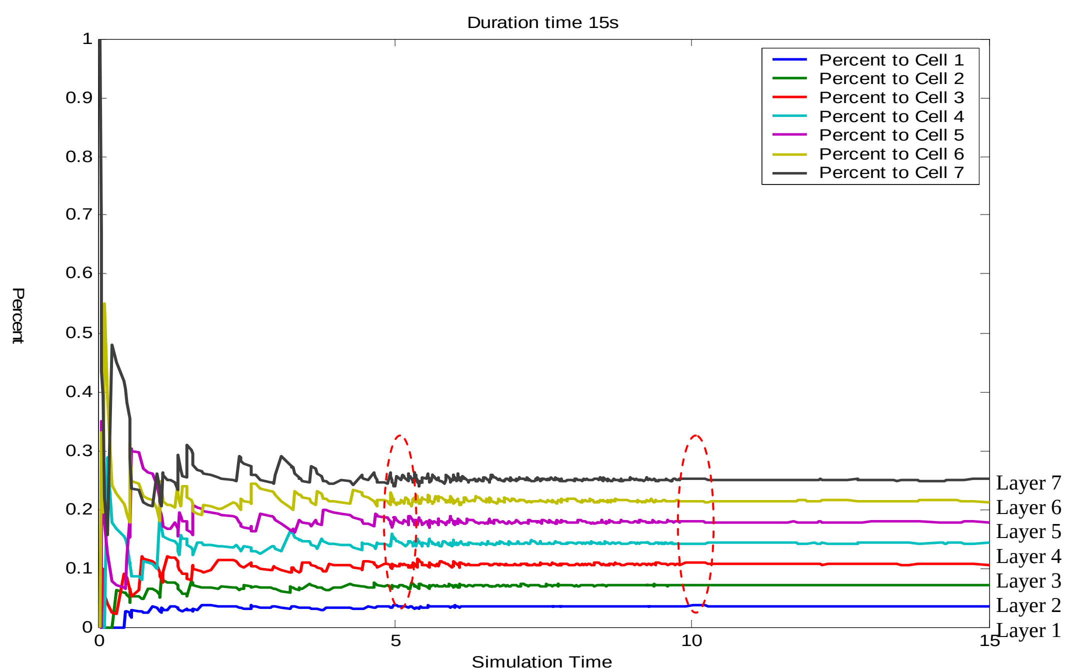


Figure 5. 9 Percentage of traffic assigned to each cell while varying inter-arrival time during one broadcast period

In the previous simulation scenario, the multiple RNs with more complicated traffic generation mode have been incorporated. There are 100 RNs randomly deployed in the 7-Cell for the first quarter of simulation duration. During the second quarter of simulation, the number of RNs is reduced to 25. Then this number rebounds back to 75 for the third quarter of simulation duration. In the last quarter of simulation, the number of RNs drops to 10. Each RN independently generates packets by a Poisson packet arrival process also with randomly varied packet length. Figure 5. 10 show the collected percentage of total load of the system distributed to each cell. As it is shown, the layer scheduling algorithm achieves the expected load-balancing even in extremely complicated traffic environment.

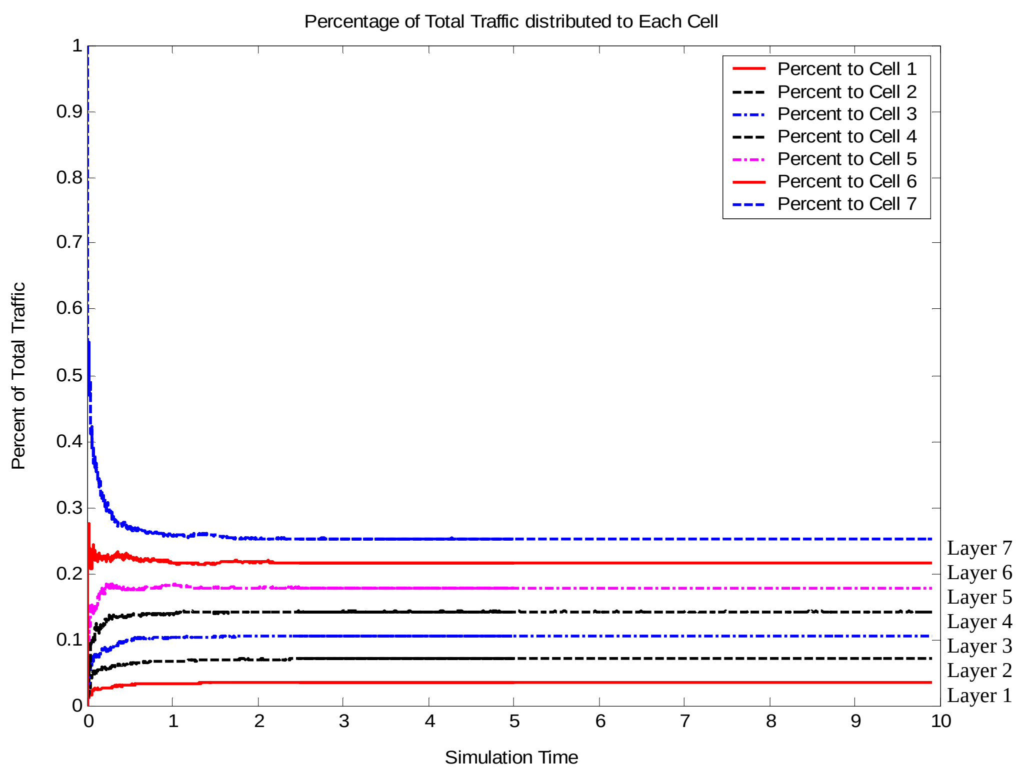


Figure 5. 10 Percentage of traffic assigned to each cell with multiple RNs

5.5 Conclusion

Load balancing is a key to maximize the capacity of the RVTNA regardless of the user distribution and the channel availability of each cell in a cellular system. Therefore, a novel layer scheduling algorithm with low complexity has been presented which achieves the perfect load balancing and improves the network power performance. The algorithm is incorporated with the hierarchical routing strategy specialized for the RVTNA. The traffic generated by end-users is forwarded by an RN to all layers proportional to the capacity of each layer. In fact, this algorithm can potentially support any form of heterogeneous networks when a mobile wireless user accesses a wired access point using multi-hop relaying while multiple access points are available. The proposed algorithm has been shown to be robust via a series of simulation experiments.

Chapter 6

Conclusion and Future Research Directions

In this Chapter, the research presented in this dissertation is summarized. During recent time, the battery life has become the main limiting factor for the functionality of mobile devices. It is because the advances in battery technology are progressing at slow pace whereas computation and communication demands by multimedia applications are at a rapid pace. Hence, in order to improve power efficiency for multimedia applications on mobile devices, complicated power management designs are investigated more by researchers and mobile industry to investigate more on.

The power management has been addressed from two approaches in this dissertation. The main emphasis of the first approach is on a power management architecture integrated with a more aggressive mode control procedure. The various hardware components on mobile devices change rapidly and even have competitive features as traditional pc does. Application processor is one example of such components. It allows the frequency of processor to be changed with proportionate reduction in voltage. This feature can yield significant energy savings. Quite a few low power mode designs are also implemented in other components. In order to benefit from those features, predominant components that contribute the maximum power consumption on mobile devices are identified first. The characteristics of main modules of multimedia applications are observed and studied through the experiments implemented in Chapter 3.

With the collected knowledge of multimedia applications, the optimized power management architecture is proposed in Chapter 4. In this architecture, power management is developed as a module, which has several functional units. Those functions adaptively cope with the workload of multimedia applications and manage all peripheral components at the same time. After the configuration of operating points for application processor and peripheral components are defined, power management module switches the system mode and operating points through proposed control strategy. The simulation shows about 44.3% power consumption improvement with the proposed power management strategy, which is a promising performance improvement for battery life.

In order to improve power efficiency further, the second approach focuses on integrating low-power strategy into the design of communication and corresponding communication networks. The transmission distance has a critical impact on power consumption between transmitter and receiver. In Chapter 5, the architecture of Real-time Video Transfer Network is proposed. It allows mobile users to communicate over shorter distances. In order to make the transmission between base station and routing nodes, a novel signaling protocol and hierarchical routing strategy are designed for both upstream and downstream data packet. The protocols implemented in upstream and downstream data packet are also utilized for layer construction and maintenance. A network with imbalance load traffic can cause issues like link quality and path stability, leading to improper power expenditure and reduced network life. In order to solve the imbalance traffic issue for Real-time Video Transfer Network, the distributed layer scheduling algorithm is proposed and developed as the routing strategy. A number of simulations with different inter-arrival times and packet sizes are implemented to test the proposed distributed layer scheduling algorithm. The result of simulation proves the the Load balancing can be achieved. With even distributed load traffic, overall power conservation of Real-time Video Transfer Network is achieved and optimized.

Future work in this field has only just begun. However, there is more work yet to be done in this research area. Due to rapidly changing hardware industry and new components with more advanced power management technology, coordination between the multimedia application and features of new components on mobile devices is needed. The integration of power management poses many new challenges when different applications and operating systems are involved. The main research threat is going to be how to balance the power performance when multimedia applications are running with other applications having different characteristics. In mobile multimedia environment, the main challenge in delivering multimedia to mobile devices using the wireless streaming is to ensure the quality of experience that meets the users' expectations, within reasonable power budgets, while supporting heterogeneous platforms and wireless network conditions.

There are number of ways that the simulations used in this dissertation can be extended to provide more complete characterization of the behavior of power management control strategy. For example, it would be very interesting to employ more realistic operating points and different frequency change strategies. We plan to investigate those fields in the future.

Another important direction for extending simulations is to find better ways to compare the strategies with each other. The different designs of the algorithms make it highly nontrivial to compare them along with power consumption. There remains a significant amount of work to be done in this regard.

Additionally, the performance of the load-balancing algorithm proposed in this dissertation must be evaluated in a real network environment within a large scale in future work. In addition to addressing the issues described in chapter 5, the effects of mobility and exploring methods to enhance protocol efficiency must be investigated at all networking layers from the link layer to the application layer. Extending the network architecture presented in Chapter 5 to next generation wireless network is also the subject of future research. As we have seen in our literature review, this is a difficult problem to solve.

Another critical area for research would be to make Real-time Video Transfer Network itself more dynamic by letting routing nodes to move around. This would enable us to more accurately characterize properties such as convergence of the algorithms. The current state of the art involves developing well-informed heuristics based on the analysis of simplified models of the wireless environment. The extraneous interference, a stochastic wireless channel model and drop of communication path are not covered in this dissertation. However, in real wireless environment, those factors cannot be ignored and should be incorporated into simulation and mathematical analysis. We hope to push the state of the art in this field further.

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