# Performance Enhancement in Heterogeneous Wireless Networks:

## Channel Assignment considering Switching Overhead, Query Processing using Event Signatures, and Uplink Traffic Analysis

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# Abstract

**Performance Enhancement in Heterogeneous Wireless Networks:**
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As new Radio Access Technologies have been constantly developed and deployed with various emerging multimedia applications and multi-radio portable devices, the level of heterogeneity in wireless networks has been increasing. Since current wireless network technologies have their own unique characteristics and capabilities, radio resource sharing and information processing in heterogeneous environments is widely considered to be crucial in optimizing the network throughput and capacity. Furthermore, new trends in the use of the Internet due to the emergence of new services and changes in the propensity of mobile users make heterogeneous resource management problems increasingly difficult. In this dissertation, these three concerns are addressed in order to achieve significant performance enhancement in terms of network management and user satisfaction.

First, resource allocation and scheduling problems in multi-radio multi-channel Wireless Mesh Networks are addressed by considering the switching overhead incurred from switching radios dynamically from one channel to another. We explicitly model the switching delay that is incurred during channel switching and use that delay in the design of channel assignment algorithms. Both centralized and distributed channel assignment algorithms are provided. Performance of the developed channel assignment algorithms is analyzed through discrete-event simulations.

Second, the problem of information processing in Heterogeneous Wireless Sensor Networks is considered. As a powerful application domain of information processing, we

consider the problem of identifying significant events using diverse sensors deployed in the area. We provide a mechanism by which sensors can exchange information using signatures of events instead of raw data to save on transmission costs. Further, we present an algorithm that dynamically generates phases of information exchange based on the cost and selectivity of each sensor filter. Simulation results show that the proposed algorithm detects events while minimizing the transmission and processing costs at sensors.

The new trend in wireless services is shifting from downlink-centric services to bidirectional and uplink centric services. Through the popularity of social networking services (e.g. Facebook, YouTube, and Flickr), we are observing an ever-increasing amount of user-generated content, also known as user-created content. This recent uplink traffic pattern is considered as a final problem in this dissertation. Live uplink traffic traces obtained by monitoring 3G networks of a mobile data service provider are analyzed. The results using six different self-similarity analysis algorithms suggest that this uplink traffic is self-similar. The impact of analyzed traffic characteristics on mobile data networks is evaluated in the WiMAX module available in OPNET software.

The contributions of this dissertation research lie in the area of radio resource management, distributed information processing, and new traffic pattern analysis in heterogeneous wireless networks. This work is the first to investigate the three crucial factors that limit network throughput and capacity, and analyze their impact on network performance in heterogeneous environments. Our consideration of switching overhead and use of sensory signatures are novel contributions and achieve significant performance enhancement in heterogeneous wireless networks.

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# Chapter 1

# Introduction

## 1.1 Motivation

As new Radio Access Technologies (RATs) have been constantly developed and deployed with various emerging multimedia applications and multi-radio portable devices, the level of heterogeneity in wireless networks has been increasing. Since current wireless network technologies have their own unique characteristics and capabilities, radio resource sharing and information processing in heterogeneous environments is widely considered to be crucial in optimizing the network throughput and capacity. Furthermore, new trends in the use of the Internet due to the emergence of new services and changes in the propensity of mobile users make heterogeneous resource management problems increasingly difficult. In this dissertation, these three concerns are addressed in order to achieve significant performance enhancement in terms of network management and user satisfaction.

In heterogeneous networks, transmitting huge volumes of data efficiently is a major problem in terms of resource sharing over different frequency bands and networks. More and more users are generating and publishing their own real-time multimedia data, and various emerging devices are collecting and distributing real-time physical data. Consequently, delivering large amounts of real-time data successfully throughout heterogeneous wireless networks is a critical and difficult problem in optimizing the network throughput and interference. As Heterogeneous Wireless Mesh Networks (HWMNs) are envisioned as one of the key infrastructures in the next generation of wireless networks [RDV$^+$05], we consider channel assignment and scheduling in multi-radio multi-channel HWMNs.

When we consider highly resource-constrained heterogeneous environments, information processing is another critical problem in terms of minimizing the transmission and processing costs, thereby extending the life of the network. As a powerful application domain of information processing, event detection in sensor networks has received much attention in the wireless research community. Detecting an event using distributed query processing in a strictly constrained and highly heterogeneous sensor network is a significant challenge. This event detection scheme can be applied in a broad spectrum of application domains such as health care systems and battlefields. For these reasons, we consider the problem of identifying significant events in Heterogeneous Wireless Sensor Networks (HWSNs).

The new trend in wireless services is shifting from downlink-centric services to bidirectional and uplink centric services. Through the popularity of social networking services (e.g. Facebook, YouTube, and Flickr), we are observing an ever-increasing amount of user-generated content (UGC), also known as user created content (UCC) [fECoO]. These new uplink traffic patterns should be considered as a crucial problem for achieving significant performance enhancement in emerging heterogeneous environments.

Motivated by the above issues, this research investigates major factors that limit network throughput and capacity, develops new schemes with the aforementioned factors explicitly considered, and analyzes their impact on network performance in heterogeneous wireless networks.

## 1.2 Heterogeneous Wireless Networks

Today's advanced portable devices including smartphone are popularized with multiple wireless interfaces such as 3G, 802.11 WiFi, Bluetooth, 802.16 WiMAX etc. Before we discuss the challenging issues in heterogeneous wireless netwoeks, we briefly give an overview of current wireless technologies.

- **Wireless PAN**

  Wireless Personal Area Networks (WPANs) interconnect devices around an individual person's workspace. Typically the maximum communication ranges of WPAN is about 10 meters. IEEE 802.15.1 (Bluetooth), 802.15.3 (Ultra Wide Band (UWB)), and 802.15.4 (ZigBee) support WPAN applications. Table 1.1 shows the main characteristics of the WPAN technologies as specified in the IEEE 802.15.

- **Wireless LAN**

  Wireless Local Area Networks (WLANs) interconnect devices in local area within about 100meters. The IEEE 802.11 group of standards specifies the technologies for WLANs. Table 1.2 shows the main characteristics of the WLAN technologies as specified in the IEEE 802.11.

Table 1.1: WPAN Standards

| Standard | Frequency Band | Maximum Range | Maximum data rate | Access Method | Modulation Method |
|---|---|---|---|---|---|
| 802.15.1 (Bluetooth) | 2.4GHz | 10meters | 3Mbps | FHSS | GFSK, 2PSK, DQSP, 8PSK |
| 802.15.3 (UWB) | 3.1-10.6 GHz | 10meters | 55Mbps - 1Gbps | DS-UWB, OFDM | OPSK, BPSK, OOK, PAM, PPM, BiPhase |
| 802.15.4 (ZigBee) | 868MHz, 902-928MHz, 2.4GHz | 100meters | 250Kbps | DSSS | BPSK (868/928MHz) OPSK (2.4GHz) |

- **Wireless MAN**

  Wireless Metropolitan Area Networks (WMANs) are wireless networks that typically cover a metropolitan area or campus. IEEE 802.16 defines the WMAN technology which is called as WiMAX. Table 1.3 shows the main characteristics of the WMAN technologies as specified in the IEEE 802.16.

- **Wireless WAN**

  Wireless Wide Area Networks (WWANs) provide regional, nationwide and global wireless coverage. WWAN can achieve Internet connectivity through using cellular tower technology or satellite technology.

In this heterogeneous environment, interworking between different network types is inevitable. Various interworking strategies are reported in the literature [FSA10], [Sal04], [AHP03], [ZGLC03]. In [FSA10], authors identified the four interworking levels based on the level of service integration among networks and provided interworking mechanisms that constitute the basic building blocks in each level. More specifically, [Sal04] proposed

Table 1.2: WLAN Standards

| Standard | Frequency Band | Maximum Range | Maximum data rate | Access Method | Modulation Method |
|---|---|---|---|---|---|
| 802.11a | 5.8GHz | 100meters | 54Mbps | OFDM | BPSK, QPSK, 16-QAM, 64-QAM |
| 802.11b | 2.4GHz | 100meters | 11Mbps | DSSS, CCK | DPSK, DBPSK, DQPSK |
| 802.11g | 2.4GHz | 110meters | 54Mbps | OFDM | BPSK, QPSK, 16-QAM, 64-QAM, DBPSK, DQPSK |
| 802.11n | 2.4-5.8GHz | 160meters | 248Mbps | MIMO | BPSK, QPSK, 16-QAM, 64-QAM |

Table 1.3: WMAN Standards

| Standard | Frequency Band | Maximum Range | Maximum data rate | Access Method | Modulation Method |
|---|---|---|---|---|---|
| 802.16d (Fixed WiMAX) | 2-66GHz | 31miles | 134Mbps | MIMO-SOFDMA | QPSK, QAM |
| 802.16e (Mobile WiMAX) | 2-11GHz | 31miles | 15Mbps | MIMO-SOFDMA | QPSK, QAM |

some techniques and architectures for IEEE 802.11 WLANs and 3G cellular network integration. As the development of interworking solutions for heterogeneous wireless networks has been spurred, IEEE 802.21 working group has started work from March 2004 to enable seamless Media Independent Handover (MIH) and interoperability between heterogeneous network types including both 802 and non 802 networks [TOF$^+$09].

Within these interworking architectures, multi-access management is a key issue to provide seamless connectivity and efficient radio resource utilization in Always-Best-Connected

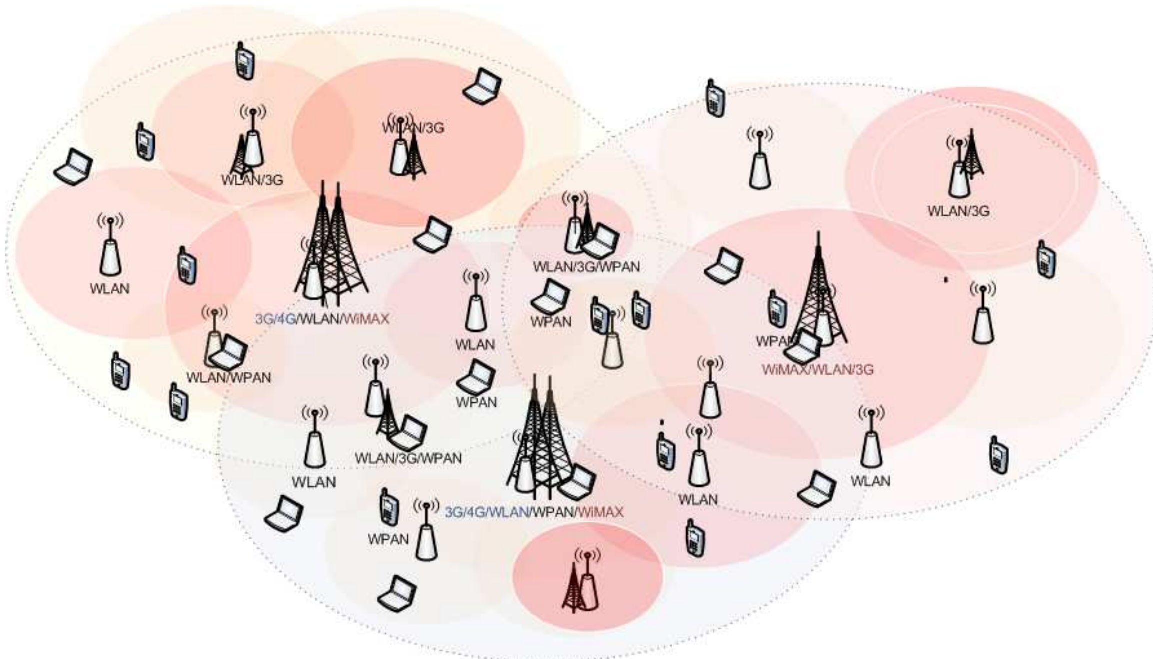



Figure 1.1: Heterogeneous Wireless Networks

paradigm [GJ03]. Sachs et al. [SPG09] proposed a general multi-access management framework which includes the different multi-access functions such as access detection, access selection and access handover. In the literature [OK10], [KMR$^+$01], [YMM09], access selection or RAT selection problem including vertical handover has been considered as a fundamental problem. In [GPRSA08], authors proposed a Markovian approach based analytical model for RAT selection policies, and showed the validation and suitability of the proposed model with 3GPP standardized technologies GSM/EDGE [HMG02] and UMTS [HT02]. With considering initial RAT selection at a call or session establishment, Gelabert et al. [GSPRA09] considered potential QoS failure due to intrinsic dynamics of the network, called radio access congestion.

In the following subsections, various types of heterogeneous wireless networks are introduced.

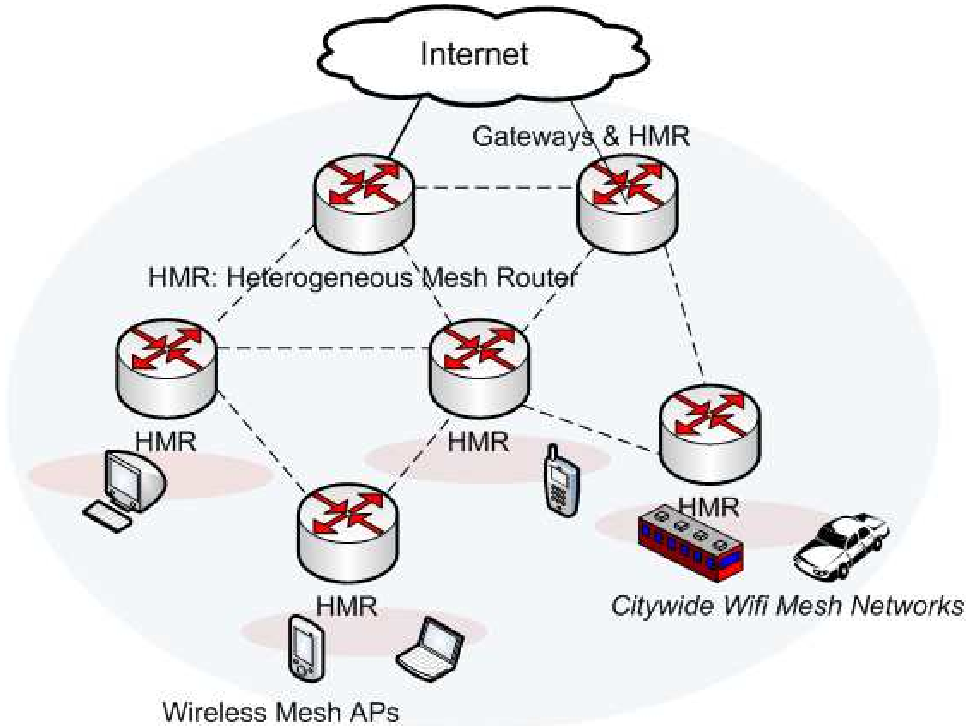



Figure 1.2: Heterogeneous Wireless Mesh Networks

### 1.2.1 Heterogeneous Wireless Mesh Networks

Heterogeneous Wireless Mesh Networks (HWMNs), envisioned as one of the key infrastructures in the next generation wireless networks. As shown in Fig. 1.2, HWMNs consist of gateways, mesh routers, and mesh clients. Heterogeneous Mesh Routers (HMRs) connect to each other and forward packets to the destination using multi-hop routing, and provide network access service to mobile mesh clients. Some HMRs which connect the Internet with wired connection will serve as gateways. Since HWMNs can be deployed quickly with low initial capital expense and provide highly flexible and reconfigurable wireless links over large areas, HWMNs are considered as a promising wireless broadband networks for various applications such as Public Safety Networks, Municipal Broadband

Internet Access, and Mobile Telephony Backhaul Networks.

According to Muniwireless [Bro], there are more than hundreds metro-scale WiFi mesh projects currently underway or in the planning stage, and we expect this number to grow dramatically over the next few years. Furthermore, current telecommunication service providers have deployed 4G (WiMAX and LTE) technologies already, and there are numerous industry-projects and academic-studies on their interworking architectures and mechanisms [Com],[FDAI+10],[LLCM08],[CMGK08].

### 1.2.2 Heterogeneous Wireless Sensor Networks

Wireless Sensor Networks (WSNs) consist of a large number of small devices with various sensing capabilities. Typically wireless sensors monitor physical or environmental conditions including temperature, light, sound, or motion, and transmit monitored physical data through the wireless networks. As the technology of microelectronics and wireless communications is rapidly developing, WSNs have been considered as a promising wireless infrastructure for various application domains. Examples of such applications range from a controlled domain such as homes, hospitals, or offices to an uncontrolled domain such as battlefield or disaster areas.

Current available multimedia wireless motes are shown in Table 1.4 [AGZAKMP10]. As advanced multimedia sensors and wireless technologies are developing, the level of heterogeneity of WSNs is rapidly increasing. In Heterogeneous WSNs (HWSNs), sensor nodes have different capabilities on power, computation, and communication. Because of this heterogeneity, diverse data processing and efficient transmission schemes should be designed carefully in HWSNs.

Table 1.4: Wireless Multimedia Motes

| Platform | Processor | Memory RAM | Camera | Radio | Power |
|---|---|---|---|---|---|
| Cyclops | 8-bit ATMEI | 64KB | Agilent compact CIF | 802.15.4 | 110mW-0.76mW |
| Imote2 +Cam | 32-nit PXA271 | 256KB | IBM400 camera | 802.15.4 | 322mW-1.8mW |
| MeshEye | 55MHz 32-bit ARM7TDMI | 64KB | Agilent ADNS-3060 | 802.15.4 | 175.9mW-1.78mW |
| Panoptes | 400MHz 32-bit PXA255 | 64MB | Logitech 3000USB | 802.11 | 5.3W-58mW |
| MicrelEye | 8-bit ATMEL | 36KB +1MB SRAM | Omnivision OV7640 | Bluetooth | 500mW |
| CITRIC | 624MHz 32-bit PXA270 | 64MB | Omnivision OV9655 | 802.15.4 | 1W |
| Fox +Cam | 100MHz LX416 | 16KB | Labtec Webcam bro | Bluetooth | 1.5W |

## 1.3 Scope of Research

In this dissertation research, we focus on three problems that can impact network performance in heterogeneous wireless networks.

First, the problem of resource allocation and scheduling in multi-radio multi-channel mesh environment are considered. The switching overhead is explicitly modeled and channel assignment algorithms are designed by considering that switching overhead.

Second, the problem of information processing in heterogeneous sensor networks is considered. We provide an event detection mechanism by which sensors can exchange information using signatures of events instead of raw data to save transmission costs.

Last, a recent uplink traffic pattern is considered. Live uplink traffic traces obtained by monitoring 3G networks are analyzed, and their impact on network performance is evaluated.

The scope of this research is outlined as follows.

**1. Channel Assignment considering Switching Overhead in HWMNs**

- The switching overhead that is incurred during channel switching is modeled , channel assignment algorithms are designed by using that delay.
- We extend existing algorithms in the literature, namely Greedy Maximal Scheduling (GMS) and Distributed Maximal Scheduling (DMS) [LR07], taking the switching delay into account in the channel assignment.
- Performance of the developed algorithms is analyzed through discrete-event simulations.

**2. Event Detection using Sensory Signatures in HWSNs.**

- We consider the problem of identifying significant events using sensors deployed in the area.
- We provide two protocols that can reduce the computation cost and the communication cost for the sensor network, thereby extending the life of the network. The suggested protocols employ three main techniques to reduce these costs:
  (i) use of sensory signature to avoid sending raw or processed data
  (ii) use of phases to avoid unnecessary computations

(iii) use of leader nodes to avoid unnecessary communications.

- Performance of the developed protocols is analyzed through discrete-event simulations.

**3. Uplink Traffic Pattern in Mobile Data Networks.**

- We analyze uplink traffic collected from MMS services in WCDMA networks of SK Telecom, Korea.
- Six different self-similarity analysis algorithms are used.
- The impact of this characteristics on mobile data networks is evaluated through the WiMAX module available in OPNET software.

## 1.4 Dissertation Outline

This dissertation document is organized as follows: Chapter 2 presents key issues in various heterogeneous environments and the relevant literatures. Chapter 3 presents channel assignment algorithms considering switching overhead in multi-radio multi-channel HWMNs. After discussing the role of switching overhead and showing why it is necessary to consider the effects, we extend existing algorithms taking the switching delay into account in the channel assignment. At last, performance analysis through discrete-event simulations is given. Chapter 4 presents event detection protocols using sensory signatures and distributed query processing in HWSNs. By using sensory signatures and phases, the communication cost and the computation cost are significantly reduced. In chapter 5, we analyze live traffic traces of uplink traffic and discuss its self-similar characteristics. As the simulation results, we present the impact of the data burst on the network performance through trace-driven OPNET simulation. Finally in chapter 6, concluding remarks are made and future directions are pointed out.

# Chapter 2

# Literature Survey

## 2.1 Channel Assignment in Heterogeneous Wireless Mesh Networks

In Wireless Mesh Networks (WMNs), channel assignment problem can be defined as finding a proper mapping between the available channels and the radios at each node such that the network performance is optimized. Thus channel assignment and scheduling methods are widely considered to be crucial in optimizing the network interference and throughput.

As shown in Fig. 2.1, mesh routers can be equipped with multiple radios operating in multiple non-overlapping channels. By assigning different channels to radio interfaces in the interference range, multiple channel-interface pairs can be served simultaneously, and this leads to higher network capacity. In this multi-radio multi-channel environment, a proper assignment of channels to interfaces is a critical factor of resource allocation

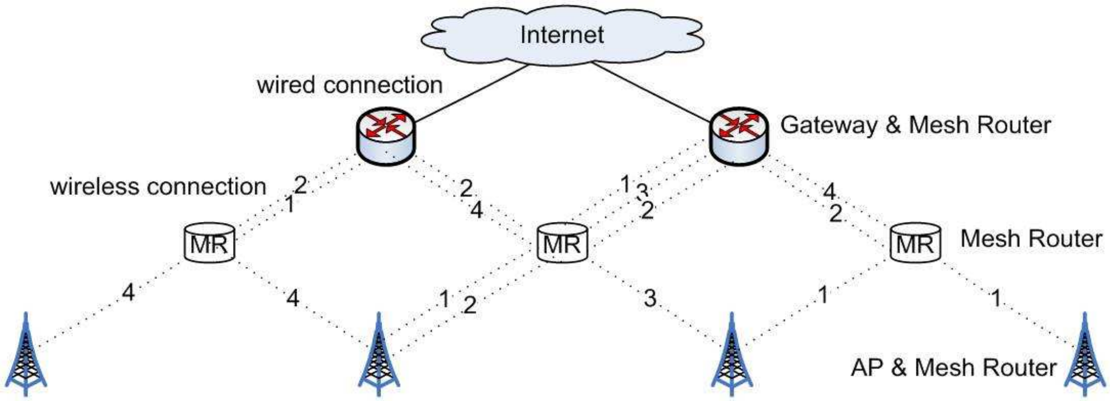



Figure 2.1: Channel Assignment in Wireless Mesh Networks

problem [RDV+05].

Channel assignment schemes can be divided into three categorizes: fixed, dynamic, and hybrid assignment [SGD+07]. Fixed schemes assign channels to radio interfaces statically [RGcC04], [KV05], [MD05] and are adequate for use when the network condition is stable. In order to consider significant changes to traffic load or network topology in fixed schemes, quasi-static channel assignments are proposed in [JZ08] and [SGDC08]. Quasi-static schemes allow the channel assignment changes, but infrequently, resulting in negligible traffic measurement overheads and switching delays. Dynamic assignment schemes change the assignment as needed, per packet or time slot [RC05]. Since radio interfaces can frequently switch from one channel to another, dynamic schemes can accommodate the changes in network conditions. However channel switching delays (typically 802.11 card has a few hundreds of microseconds to a few milliseconds) can be a challenging problem [SGD+07], [VKLS06], [FLW08]. Hybrid strategies combine static and dynamic assignment concepts by using static assignment for certain nodes/radios, and using a dynamic assignment approach for the other nodes [KV05], [KV06], [RBAB06].

## 2.2 Event Detection in Heterogeneous Wireless Sensor Networks

In Wireless Sensor Networks (WSNs), information processing is a critical problem due to the huge volume of real-time physical data collected through many diverse sensors [ZG04]. As a powerful application domain of information processing, event detection in sensor networks has received much attention in the wireless research community. The literature provides various event detection schemes, as in [LWHS02], [KI04], and [BRS03]. In these event detection projects, events are typically categorized into two groups: atomic events and compound events defined by [PKRVJ05] and [LLS$^+$04]. An atomic event is an event characterized by a single type of physical data, while a compound event is one characterized by multiple types of physical data. Even detecting an atomic event in a constrained network is a significant challenge. Marticic et al. in [MS06] present a distributed event representation paradigm. This paradigm divides the detection area into cells, gathers data from all nodes in each cell, and computes a weighted average of all data gathered within the cell. Sensor nodes store copies of adjacent cell averages, and can detect an event by matching this submatrix of cell averages to an event signature. Hu et al. in [HY07] present a sleeping schedule to reduce communication and computation overhead, improve energy efficiency and prolong the life of the network. By deploying multiple sensors to monitor the same area and electing a single node to monitor the area, a large fraction of nodes can remain asleep while still ensuring that the area is monitored. For compound events, Abadi et al. extend the TinyDB query processor in [MFHH05] to produce an event detection system for sensor networks called REED, presented in [AML05]. The system supports in-network joins between sensory data and static tables built outside the sensor network. Kumar et al. in [PKRVJ05] propose a distributed event detection framework by considering collaboration among sensor nodes. The framework forms a group of sensor nodes gathering all data types necessary to detect a compound event, and each group reports to the centralized headquarters if the aggregated data satisfies the given conditions.

Previous work considering sensor networks in battle environments include [OUS$^+$08], [SML$^+$04], and [WSS03]. Especially the Battle of the Water Sensor Networks (BWSN) was held in August 2006. After the events of September 11, 2001, in the United States, more practical research and performance analysis on water distribution systems are demanded against possible chemical attacks, so that fifteen sensor network designs considering the following four design objectives are proposed in BWSN [OUS$^+$08]: 1) minimization of the expected time of event detection, 2) minimization of the expected population affected prior to event detection, 3) minimization of the expected demand of contaminated water prior to event detection, and 4) maximazation of the detection likelihood.

In the case of battle event detection, sensors can be deployed in a battlefield, gathering several types of data. The sensors can take the form of smoke-detectors, noise-detectors, motion-detectors, as well as cameras. We would like to match data gathered around the same time and location to identify significant events that are characterized by specific sensory data and to alert a centralized headquarters about the occurrence of the significant events so that they can respond appropriately to the events. The type of events that we would like to identify can vary; for example, a significant event might be the explosion of a bomb or the deployment of a chemical agent. Each event is characterized by a particular set of sensory data, or “sensory signature”. For example, an exploding bomb might be characterized by a bright light, loud sound, and hot temperature, and its sensory signature would reflect these properties.

## 2.3 UGC Traffic and Mobile Data Networks

### 2.3.1 User-Generated Content

Web 2.0 does not refer to a new technology or technical specification, but to changes in web-based environment which software developers and end-users use as a platform. The basic idea of this Web 2.0 is empowering computer end-users to contribute to develop, share, and evaluate information efficiently in Internet. As a part of Web 2.0 concept, user-generated content (UGC), also known as user-created content (UCC) or consumer generated media (CGM), is growing rapidly and making a new producing trend of media content [fECoO]. In other words, as opposes to traditional media producers, end-users are generating multi-media contents and uploading them to websites such as YouTube, Facebook, Wikipedia, MySpace, Flickr, and so on. These changes in web-based communities are emerging not only in wired networks, but also in wireless networks. In cellular networks, especially, as being upgraded to 3G technologies the study on modeling and analysis of new traffic pattern of UCC is required.

### 2.3.2 Mobile Network Evolution: Towards Uplink Enhancement

Fast growth in cellular usage with emerging multimedia applications have led to the requirement for new 3G cellular telecommunication networks. To deal this requirement, two new partnership projects, 3rd Generation Partnership Project (3GPP) and 3GPP2, were established in 1998 [3GPa][3GPb]. 3GPP is developing 3G standard for Global

System for Mobile (GSM) based system such as General Packet Radio Service (GPRS) and Universal Mobile Telecommunications System (UMTS)( or Wideband Code Division Multiple Access (WCDMA)) and 3GPP2 is focusing on Interim Standard (IS)-95 based CDMA system such as CDMA2000. As high data rate services such as video transmission and other data services became popular, both 3GPP and 3GPP2 introduced downlink enhancement technologies of each 3G system (WCDMA, CDMA2000), which are High Speed Downlink Packet Access (HSDPA)(up to 10Mbps) and CDMA 1x Evolution Data Only (EvDO) (up to 2.4 Mbps in Rev. 0) respectively [HT06][FGB$^+$05].

Initially most of 3G applications were considered to have much heavier traffic in the downlink direction than in the uplink direction. However, as new services such as video telephony and FTP upload are introduced and a new uploading pattern such as UCC emerged, uplink enhancements have also received great attention making High Speed Uplink Packet Access (HSUPA) and CDMA 1x EvDO Rev. A system considered in 3.5G systems [SK05][EVD06].

The CDMA 1x EvDO Rev. A system was standardized in March 2004. The peak rate can achieve up to 3.1Mbps for the downlink and 1.8Mbps for the uplink. A novel flow-centric protocol design is adopted to enhance the system's capability for satisfying different flow QoS requirements. Improvement has been observed in supporting delay-sensitive applications and providing tradeoff in delay, capacity and physical-layer error-rate [FGB$^+$05].

HSUPA was introduced to improve the capacity of WCDMA uplink in 3GPP Release 6 with the first specification version in December 2004. Although HSUPA is the commonly used terminology, Enhanced-Dedicated Channel (E-DCH) is the official term used by 3GPP to describe the new uplink transport channel [HT06]. The E-DCH supports fast Node B based uplink scheduling, fast physical layer hybrid ARQ (HARQ) retransmission schemes and, optionally, a shorter transmission time interval (TTI) (2ms) to reduce delays, increase the data rate (up to 5Mbps) and improve the capacity of the uplink [PEHS04].

WiMAX 802.16 has become the most promising broadband wireless access technology. In Oct 2007, WiMAX is officially accepted as the one of the 3G standards by International Telecommunication Union (ITU). The standard of WiMAX evolved from the original 802.16 to the latest 802.16e which supports full mobility. When the Orthogonal Frequency-Division Multiple Access (OFDMA) physical layer is employed, the theoretical uplink or downlink raw bitrate could achieve 70Mbps [Nua].

# Chapter 3

# Channel Assignment considering Switching Overhead in HWMNs

## 3.1 Channel Assignment and Switching Overhead

### 3.1.1 Related Work

A vast amount of research has been conducted to exploit multiple channels for performance improvement. Ramachandran et al. [RBAB06] proposed a centralized channel assignment algorithm which has a Channel Assignment Server (CAS). CAS allocates channels to radio interfaces while minimizing interference in multi-radio multi-channel WMNs. Among the centralized algorithms, an optimum scheduling policy was given by Tassiulas et al. in their seminal paper [TE92]. This scheduling policy, commonly referred to as Maximum Weighted Scheduling, is computationally prohibitive for general interference models (such as 2-hop interference model), and a simpler but suboptimal strategy called GMS is well established as a scheduling algorithm for single channel multi-hop wireless networks. GMS has been known to have an efficiency ratio of $1/\kappa$ in single-channel networks [LS06] and $1/(\kappa+2)$ in multiple-channel networks [LR07], where $\kappa$ is the interference degree of the network [CKS05], [Cha06]. Very recently, insights into the true efficiency ratio of GMS have been presented in [JLS09], where authors showed that the efficiency ratio of GMS is equal to a network property (pooling factor). They also showed that the worst-case efficiency ratio of GMS in geometric network graphs is between $\frac{1}{6}$ and $\frac{1}{3}$.

In distributed algorithms, Joo [Joo08] proposed a simple distributed scheduling algorithm for single channel wireless networks, which achieves an efficiency ratio no smaller than GMS. In [LR07], Lin et al. suggested a distributed algorithm for multi-channel network with low-complexity that has the same level of efficiency ratio as GMS. Ko et al. [KMPR07] also proposed a distributed channel assignment algorithm with channel interference cost function which indicates the spectral overlapping level between channels. Generally, distributed algorithms can only achieve a fraction of the maximum possible throughput due to the lack of complete information. To provide the higher throughput in distributed schemes, Brzezinski et al. [BZM08] proposed algorithms for pre-partitioning a mesh network into smaller subnetworks in which simple distributed scheduling algorithms can achieve the maximum capacity.

In addition, much of the recent research on multi-radio multi-channel WMNs has dealt the channel assignment and routing problem jointly as a challenging cross-layer problem [LR07], [NGES07], [TT07]. Raniwala et al. [RGcC04] showed significant improvement of the overall network goodput in 802.11 based multi-channel WMN architecture by considering channel assignment and routing jointly. In [LR07], authors proposed a distributed channel scheduling algorithm that guarantees the efficiency ratio to be same as the centralized GMS algorithm in multi-channel wireless networks.

Recently switching overhead has been acknowledged as a factor for channel assignment and routing problems in multi-radio WMNs. However, none of existing schemes considers the switching overhead in channel assignment algorithm itself. In [FLW08], Feng et al. suggested a hybrid channel assignment protocol (HCAP) to find out a reasonable tradeoff between flexibility and switching overheads. In order to avoid frequent interface switching, HCAP adopts static assignment for nodes that have the heaviest loads. In [FLW09], authors considered switching overhead as a key factor to estimate interference level of a node/link.

### 3.1.2 Switching Overhead - Negligible or not?

In multi-radio multi-channel environment, many channel assignment algorithms need frequent channel switching to optimize the efficiency of WMNs. However channel switching incurs some non-negligible delay, which leads to accumulation of switching delays between end to end nodes.

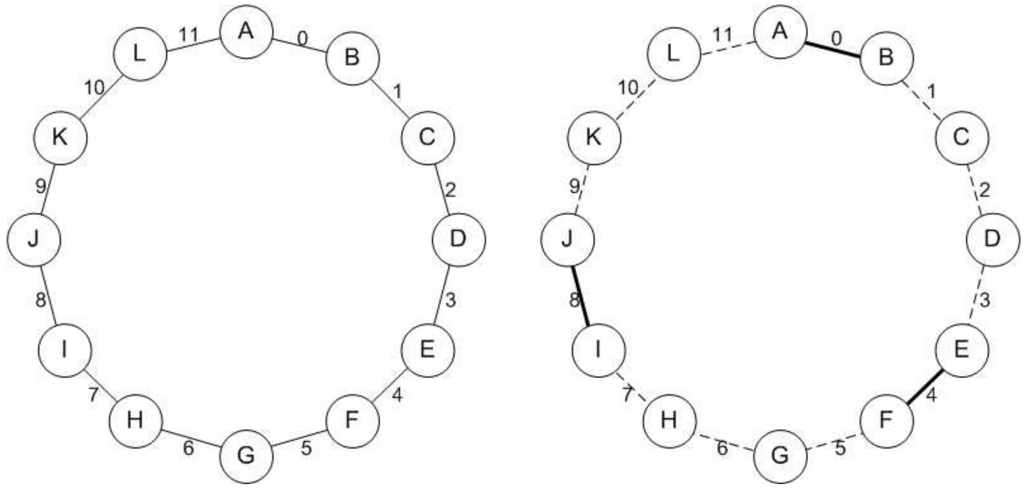
In a 802.11 card, the hardware switching delay is typically in the order of a few hundreds of microseconds to a few milliseconds [RC05], [VKLS06]. When a packet of $1024$ bytes is transmitted through 802.11a/b network where the typical transmission rate is about 25Mbps/6Mbps, it takes $1024 \times 8/(25 \times 10^6) = 328\mu s$ or $1024 \times 8/(6 \times 10^6) = 1.3ms$, which are in the same range of 802.11a/b switching delay. Furthermore when switching occurs across different frequency bands (e.g., 5GHz for 802.11a and 2.4GHz for 802.11b/g) the impact of switching delay on the overall network performance becomes even more significant. In [KV05], Kyasanur and Vaidya showed that the switching delay degrades the network capacity as a function of $\frac{S}{S+T}$ (where $S$ is switch delay and $T$ is transmission time). As in the example above, the value of $S$ can approach the value of $T$. This causes a significant degradation in network capacity.

With technology advancements, it is expected that the switching delay will become smaller overtime [BCD04]. However, the switching delay can be expressed in terms of packet duration as $d_t \times L/P$, where $d_t$ is the hardware switching delay, and $P$ and $L$ are the packet size and transmission speed respectively. While the hardware switching delay can be expected to progressively get smaller, the transmission speeds can be expected to progressively get larger. Thus, the trend on the overall loss of bandwidth due to the switching delay is difficult to predict due to this "push-pull" effect of technology. This highlights the need to design channel assignment schemes that consider the delay induced due to the switching overhead, and to model their performance as a function of the switching overhead.

### 3.1.3 Shortcomings of GMS with Switching Overhead

It has been shown in [JLS09] that the worst-case efficiency ratio of GMS in geometric network graphs is between $\frac{1}{6}$ and $\frac{1}{3}$. In our earlier work [YZAC09], however, we indicated that when switching overhead is considered, GMS algorithm may have no provable efficiency ratio. Next, we present a counterexample which shows that the efficiency ratio of GMS algorithm can be arbitrarily close to $0$ when switching overhead $\delta$ is considered in a network with $2$-hop interference model.

Consider the network topology as shown in Figure 3.1. We assume that the traffic moves in clockwise direction, all link capacities are $4$ and the initial queue size is $\chi + 3$ at nodes $A$, $E$ and $I$, $\chi + 2$ at nodes $B$, $F$ and $J$, $\chi + 1$ at nodes $C$, $G$ and $K$, and $\chi$, at nodes $D$,




(a) Topology (b) Initial schedule

Figure 3.1: Example topology and schedule with GMS

$H$ and $L$, where $\chi$ is a large number. Consider that all nodes have a constant arrival rate of $1-\delta+\epsilon$, where $\epsilon$ is a small number. GMS initially serves links $0$, $4$ and $8$, as the queues at the origin nodes of those links are the highest and all link capacities are equal. In the next timeslot, GMS serves nodes $1$, $5$ and $9$. In the following timeslot, GMS serves nodes $2$, $6$ and $10$. followed by nodes $3$, $7$ and $11$. Then, the entire cycle repeats. During these $4$ timeslots, each node receives service over one timeslot, and is able to send $4(1-\delta)$ bits. During the same $4$ timeslots, it receives a total of $4(1-\delta+\epsilon)$ new bits from its arrival process, and thus its queue is not stable under GMS.

However, the following schedule can serve the same system with an arrival rate of $4/3-\delta$: Consider three link assignments: $\{0,3,6,9\}$, $\{1,4,7,10\}$ or $\{2,5,8,11\}$. We observe that considering the 2-hop interference model, these link assignments are valid. Start with the first one, and switch to the next one after $\chi/3$ timeslots. Thus, over $\chi$ timeslots, each node can send $(\chi/3-1)4+(1-\delta)4$ bits. During the same $\chi$ timeslots, it receives a total of $\chi(4/3-\delta)$ new bits from its arrival process, and thus its queue is stable under this channel assignment scheme.

Therefore, the efficiency ratio of GMS over this schedule is no better than $\frac{1-\delta+\epsilon}{4/3-\delta}$. Since $\delta$ can be vary between $0$ and $1$, the efficiency ratio can be arbitrarily close to $0$.

## 3.2 System Model and Problem Statement

In this section, we first describe the network model considered in this paper. Then, we present a formulation of our problem for channel assignment and scheduling.

### 3.2.1 System Model

We consider a time slotted multi-hop network modeled by an undirected graph $G = (V, E)$ where $V$ denotes the set of nodes and $E$ denotes the set of edges. For a link $l \in E$ when used in a transmission, the transmitter and the receiver nodes are denoted by $b(l)$ and $e(l)$, respectively. For a node $v \in V$, the set $E(v)$ denotes the set of edges incident on node $v$. Let $C$ denote the set of channels available in the system. Time is slotted into a unit length. Each node is equipped with at least one radio and can dynamically switch radios from one channel to another with additional overhead $\delta$ represented as a fraction of the time slot duration, i.e., $\delta = switching\ time/time\ slot\ duration$. It is assumed that each node $v$ is equipped with $\alpha(v)$ radios such that at any time, $v$ can be involved in up to $\alpha(v)$ transmissions as either transmitters or receivers.

Let $I_l$ denote the set of links that interfere with link $l$. It is assumed that during the scheduling period (i.e., over a certain period of time), the network topology is fixed; hence, the interfering set $I_l$ of link $l$ is also fixed. We assume that the interference relation is symmetrical. We denote the queue length of link $l$ in time slot $t$ by $q(l,t)$ where the queue is assumed to be corresponding to $b(l)$, that is, the transmitter node of link $l$. The rate at which link $l$ can transmit on channel $c$ is denoted by $r(l,c)$.

### 3.2.2 Problem Statement

There are $S$ users in the system. We assume that user $s$ injects packets into the system with a rate $\lambda_s$ and traffic from $s$ follows a fixed path during the scheduling period. (The routing table is assumed to be fixed during the scheduling period). Let $h(l,s) = 1$ if user $s$'s traffic traverses over link $l$, and $0$ otherwise. The evolution of $q(l,t)$ is then:

$$q(l,t+1) \quad = \quad [q(l,t) + \sum_{s=1}^{S} h(l,s)\lambda_s - D(l,t)]^+ \tag{3.1}$$

where $D(l,t)$ denotes the number of packets that link $l$ can serve in time $t$ and $[\cdot]^+$ denotes the projection to $[0,\infty)$. We say the system is stable if the queue length of each link in any time slot remains finite.

Let $\vec{\lambda} = [\lambda_1, \cdots, \lambda_S]$ denote the traffic injected by the $S$ users into the system. The *capacity region* under a particular channel assignment and scheduling algorithm is the set of $\vec{\lambda}$ such that the system remains stable. The *optimal capacity region* $\Omega$ is defined to be the union of capacity regions of all algorithms. An algorithm is called *throughput-optimal* if it can achieve the optimal capacity region $\Omega$. The *efficiency ratio* of an algorithm is the largest number $\gamma \leq 1$ such that for any load $\vec{\lambda} \in \Omega$, $\gamma\vec{\lambda}$ is in capacity region of the algorithm.

A major component of any throughput-optimal scheduling problem is to solve an optimization problem in each time slot $t$ that maximizes $\sum_{l\in E}\sum_{c\in C} q(l,c,t)r(l,c,t)$ satisfying the given constraints. With the switching delay $\delta$ as an additional constraint, we formulate the scheduling problem as follows where $z(l, c, t) \in \{0, 1\}$ is a decision variable such that $z(l, c, t) = 1$ means that channel $c \in C$ is assigned to link $l \in E$ in time slot $t$.

**Scheduling with $\delta$:**

*Input:* $Z(t-1) = [\, z(l, c, t-1) \,]$ for all $l \in E$ and $c \in C$; $q(l, t)$ for all $l \in E$; and $r(l, c, t)$ for all $l \in E$ and $c \in C$.

*Output:* $Z(t) = [\, z(l, c, t) \,]$ where (i) $z(i, c, t) \in \{0, 1\}$, (ii) for any $l$, $l' \in E$ such that $l' \in I_l$ and $c \in C$, $z(l, c, t) + z(l', c, t) \leq 1$, (iii) for any $l \in E$, $\sum_{c \in C} z(l, c, t) \leq \min\{\alpha(b(l)), \alpha(e(l))\}$, and satisfying (i-iii), the objective is to maximize

$$\sum_{l \in E, c \in C} \{z(l, c, t) q(l, t) r(l, c, t) \mid z(l, c, t-1) = 1\}$$
$$+ \sum_{l \in E, c \in C} \{z(l, c, t)(1-\delta) q(l, t) r(l, c, t) \mid z(l, c, t-1) = 0\}$$

Note that if $z(l, c, t-1) = 1$ and $z(l, c, t) = 1$, the channel $c$ can be fully utilized on link $l$ during the time slot $t$. But if $z(l, c, t-1) = 0$, the channel $c$ when assigned to $l$ in time $t$ can be utilized for only a fraction $1 - \delta$ of the time slot.

## 3.3 Scheduling considering Switching Overhead

In this section, we extend the existing algorithms taking the switching delay into account in the channel assignment. The basic idea is to define different weight functions depending on the necessity of switching. In the following subsections, we present our centralized and distributed control algorithms beginning with the existing algorithms.

### 3.3.1 Centralized Scheduling with Switching Overhead

Greedy Maximal Scheduling (GMS) has considered as the efficient and low-complexity scheduling algorithm for both single-channel and multi-channel wireless networks [JLS09]. In this subsection, we will show the extension of GMS algorithm that considers switching overhead for multi-channel multi-radio wireless networks. In multi-channel multi-radio environment, GMS schedules link-channel pairs in decreasing order of the queue-weighted rate conforming to interference constraints. Let $\mathcal{F}$ denote the set of all link-channel pairs in a network graph $G$, i.e., $\mathcal{F} = \{(l, c)|l \in E, c \in C\}$. For all link-channel pairs $(l, c)$, $w(l, c, t)$ is defined as the queue-weighted rate $q(l, t)r(l, c)$. After finding the largest weight $w(l, c, t)$, it removes all link-channel pairs that cannot be scheduled due to $(l, c)$ being scheduled. In other words, remove from $\mathcal{F}$ all ink-channel pairs $(k, c)$ with $k \in I_l$. And if $\alpha(l) = 0$, which means link $l$ already uses up all available radio interfaces, remove from $\mathcal{F}$ all link-channel pairs $(k, c')$ with $k \in E(b(l)) \cup E(e(l))$. With the remaining pairs in $\mathcal{F}$, continue to find the largest weight until no link-channel pairs are left in $\mathcal{F}$. The detailed GMS algorithm is shown in Algorithm 1.

Considering switching overhead, the algorithm CSSO is summarized in Algorithm 2.

Our centralized algorithm considering switching overhead defines two different weight functions depending on whether or not the switching is needed. For a set of all scheduled link-channel pairs in time slot $t - 1$, i.e. $\mathcal{Z} = \{(l, c)|z(l, c, t - 1) = 1\}$, we define $w(l, c, t) = q(l, t)r(l, c)$. For a set $\{\mathcal{F} - \mathcal{Z}\}$, define $w(l, c, t) = (1 - \delta)q(l, t)r(l, c)$. In other words, we consider the switching delay factor $\delta$ as an additional factor of the weight function if the channel switching is needed when channel $c \in C$ is assigned to link $l \in E$ in time slot t. With different weight functions we use above GMS algorithm to get $Z(t)$.

**Algorithm 1** Greedy Maximal Scheduling (GMS)

```
β(v) ← α(v) for all nodes v
while size(F) > 0 do
    In F, find (l, c) with the largest weight w(l, c, t)
    z(l, c, t) ← 1
    β(b(l)) ← β(b(l)) − 1
    β(e(l)) ← β(e(l)) − 1
    for k ∈ I_l do
        remove (k, c) from F
    end for
    if β(b(l)) = 0 then
        for k ∈ E(b(l)) do
            Remove (k, c′) from F for all channels c′
        end for
    end if
    if β(e(l)) = 0 then
        for k ∈ E(e(l)) do
            Remove (k, c′) from F for all channels c′
        end for
    end if
end while
```

**Algorithm 2** Centralized Scheduling with Switching Overhead (CSSO)

For each time-slot $t$:
Let $\mathcal{F} = \{(l, c) | l \in E, c \in C\}$, $\mathcal{Z} = \{(l, c) | z(l, c, t-1) = 1\}$
Initialize $\beta(v) \leftarrow \alpha(v)$ for all nodes $v$
For $\mathcal{Z}$, define $w(l, c, t) = q(l, t)r(l, c)$.
For $\{\mathcal{F} - \mathcal{Z}\}$, define $w(l, c, t) = (1-\delta)q(l, t)r(l, c)$
**while** $size(\mathcal{F}) > 0$ **do**
    In $\mathcal{F}$, find $(l, c)$ with the largest weight $w(l, c, t)$
    $z(l, c, t) \leftarrow 1$
    $\beta(b(l)) \leftarrow \beta(b(l)) - 1$
    $\beta(e(l)) \leftarrow \beta(e(l)) - 1$
    **for** $k \in I_l$ **do**
        remove $(k, c)$ from $\mathcal{F}$
    **end for**
    **if** $\beta(b(l)) = 0$ **then**
        **for** $k \in E(b(l))$ **do**
            Remove $(k, c')$ from $\mathcal{F}$ for all channels $c'$
        **end for**
    **end if**
    **if** $\beta(e(l)) = 0$ **then**
        **for** $k \in E(e(l))$ **do**
            Remove $(k, c')$ from $\mathcal{F}$ for all channels $c'$
        **end for**
    **end if**
**end while**

### 3.3.2 Distributed Scheduling with Switching Overhead

In [LR07], a distributed joint channel-assignment, scheduling, and routing algorithm (referred here as Distributed Maximal Scheduling (DMS) is proposed. They developed a distribute scheduling algorithm for multi-channel network that can guarantee the same efficiency ratio as the centralized GMS. The main idea is to use two queueing steps to handle channel diversity. In the first step, packets arriving to each link $l$ are assigned to each channel queue (logically) to prevent links from using "weak" channels. By using the queue length information DMS logically define the number of packets that link $l$ can assign to channel $c$. In the second step, actual channels are assigned to radios according to multi-channel maximal scheduling algorithm.

In order to show the impact of switching overhead on the WMN throughput we extend their algorithm by considering switching overhead. We describe the single-path case (SP) only, but our switching overhead concept can be extended to the multi-path case.

Without the switching overhead, DMS can be summarized as follows. For each time $t$,

1. Define $x(l,c,t)$ to be the number of packets that link $l$ can assign to channel $c$ at time $t$.

   For each link $l$, $x(l,c,t)$ can be assigned as follows.

$$x(l,c,t) = \begin{cases} r(l,c), \text{if} & \frac{q(l)}{\zeta_l} \geq \frac{1}{r(l,c)}[\sum_{k \in I_l} \frac{\eta(k,c,t)}{r(k,c,t)} + \frac{1}{\alpha(b(l))} \sum_{k \in E(b(l))} \sum_{d=1}^{C} \frac{\eta(k,d,t)}{r(k,d,t)} \\ & + \frac{1}{\alpha(e(l))} \sum_{k \in E(e(l))} \sum_{d=1}^{C} \frac{\eta(k,d,t)}{r(k,d,t)}] \\ 0, & \text{otherwise} \end{cases} \tag{3.2}$$

   $\zeta_l$ is an arbitrary positive constant chosen for link $l$. The per-channel queue $\eta(l,c,t)$

represents the backlog of packets assigned to channel $c$ by link $l$. From $q(l)$, the number of packets assigned to each channel queue is $y(l,c,t) \in [0, x(l,c,t)]$, where $\sum_{c=1}^{C} y(l,c,t) = min\{q(l,t), \sum_{c=1}^{C} x(l,c,t)\}$.

2. Based on the channel queues $(\eta(l,c,t) + y(l,c,t))$, Multi-channel Maximal Scheduling (We use LubyMIS algorithm [Lub85]) is carried out. We define $Z^c(t)$ as the set of non-interfering links that are chosen to transmit data at channel $c$ at time $t$, i.e. $Z(t) = [Z^c(t)]$. For each channel $c$, $Z^c(t)$ consists of links $l$ that are backloged in channel $c$, i.e. $\eta(l,c,t) + y(l,c,t) \geq r(l,c)$. Further, for any backloged link-channel pairs $(l,c)$, at least one of the following is true.

    (a) Either link $l$ is scheduled in channel $c$, i.e., $l \in Z^c(t)$, or

    (b) Either link $k$ is scheduled in channel $c$, i.e., $k \in Z^c(t)$for some backloged $k \in I_l$, or

    (c) Either the transmitter or the receiver of link $l$ has used up all the radios.

Considering switching overhead, the proposed algorithm (DSSO) is summarized in Algorithm 3.

**Algorithm 3** Distribute Scheduling with Switching Overhead (DSSO) Algorithm

```
1: For 𝒵, x(l,c,t) = r(l,c) or 0
2: For {ℱ − 𝒵}, x(l,c,t) = (1 − δ)r(l,c) or 0
3: for each link l and channel c do
4:    Assign y(l,c,t) ∈ [0, x(l,c,t)]
      where Σ_{c=1}^{C} y(l,c,t) = min{q(l,t), Σ_{c=1}^{C} x(l,c,t)}
5: end for
6: for each channel c do
7:    find Z^c(t) by calling LubyMIS(G, c);
8: end for
```

For each time $t$, we have known the set $\mathcal{Z}$ of all scheduled link-channel pairs $(l,c)$ at time $t-1$

1. Define $x(l,c,t)$ to be the number of packets that link $l$ can assign to channel $c$ at time $t$.

   For the set $\mathcal{Z}$, $x(l,c,t)$ can be assigned as follows.

$$x(l,c,t) = \begin{cases} r(l,c), \text{if} & \frac{q(l)}{\zeta_l} \geq \frac{1}{r(l,c)}[\sum_{k\in I_l} \frac{\eta(k,c,t)}{r(k,c,t)} + \frac{1}{\alpha(b(l))} \sum_{k\in E(b(l))} \sum_{d=1}^{C} \frac{\eta(k,d,t)}{r(k,d,t)} \\ & + \frac{1}{\alpha(e(l))} \sum_{k\in E(e(l))} \sum_{d=1}^{C} \frac{\eta(k,d,t)}{r(k,d,t)}] \\ 0, & \text{otherwise} \end{cases} \tag{3.3}$$

   For the set $\{\mathcal{F} - \mathcal{Z}\}$, $x(l,c,t)$ can be assigned as follows.

$$x(l,c,t) = \begin{cases} (1-\delta)r(l,c), \text{if} & \frac{q(l)}{\xi_l} \geq \frac{1}{r(l,c)}[\sum_{k\in I_l} \frac{\eta(k,c,t)}{r(k,c)} + \frac{1}{\alpha(b(l))} \sum_{k\in E(b(l))} \sum_{d=1}^{C} \frac{\eta(k,d,t)}{r(k,d)} \\ & + \frac{1}{\alpha(e(l))} \sum_{k\in E(e(l))} \sum_{d=1}^{C} \frac{\eta(k,d,t)}{r(k,d)}] \\ 0, & \text{otherwise} \end{cases} \tag{3.4}$$

   $\zeta_l$ and $\xi_l$ are the arbitrary positive constants chosen for link $l$. From $q(l)$, the number of packets assigned to each channel queue $\eta_l^c$ is $y(l,c,t) \in [0, x(l,c,t)]$, where $\sum_{c=1}^{C} y(l,c,t) = min\{q(l,t), \sum_{c=1}^{C} x(l,c,t)\}$.

2. Based on the channel queues ($\eta(l,c,t) + y(l,c,t)$), Multi-channel Maximal Scheduling is carried out. We define $Z^c(t)$ as the set of non-interfering links that are chosen to transmit data at channel $c$ at time $t$, i.e. $Z(t) = [Z^c(t)]$. For each channel $c$, $Z^c(t)$

consists of links $l$ that are backloged in channel $c$, i.e., $\eta(l,c,t) + y(l,c,t) \geq r(l,c)$. And we give higher priority to the set $\mathcal{Z}$ backloged again. For any remaining backloged link-channel pairs $(l,c)$, at least one of the following is true.

(a) Either link $l$ is scheduled in channel $c$, i.e., $l \in Z^c(t)$, or

(b) Either link $k$ is scheduled in channel $c$, i.e., $k \in Z^c(t)$ for some backloged $k \in I_l$, or

(c) Either the transmitter or the receiver of link $l$ has used up all the radios.

In order to implement Multi-channel Maximal Scheduling Algorithm, we use the Luby Maximal Independent Set (LubyMIS) algorithm for each channel $c$ [Lub85]. The algorithm consists of three rounds. In the first round, each link updates their weight $w(l,c,t)$ and send to interference neighbors. If $(l,c) \in \mathcal{Z}$, $w(l,c,t) = (\eta(l,c,t) + y(l,c,t))r(l,c)$. Otherwise $w(l,c,t) = (1-\delta)(\eta(l,c,t) + y(l,c,t))r(l,c)$. By the end of the first round, links with highest weight are marked as the winner. In the second round, each winner notify their interference neighbors the fact that they have won. Thus at the end of second round, the interference neighbors knows that they are the losers. In the third round, each loser notifies its neighbors. Then all the winners, the losers, and the loser's neighbors remove the appropriate nodes and links from the graph $G$. After the third round, the algorithm repeats from the first round to find the winners, the losers, and the loser's neighbors with remaining nodes and links. This process is repeated until no links are left in $G$. Finally, LubyMIS provides $Z^c(t)$, consisting of the winners.

### 3.3.3 Stability Analysis

We prove in this section that the efficiency ratio of the proposed DSSO algorithm is $(1 - \delta)/(\kappa + 2)$, where $\kappa$ is the interference degree of the network.

***Proof:*** We show that for any $\overrightarrow{\lambda}$, such that $\overrightarrow{\lambda}(\kappa + 2)/(1 - \delta)$ can be served by a scheduling algorithm, then $\overrightarrow{\lambda}$ can be served by DSSO.

As outlined in [LR07], one key to observing this is first note that there must exist some $\tilde{x}(l, c) \in [0, r(l, c)]$ such that:

$$\frac{(1+\epsilon)^2(\kappa+2)}{1-\delta}\sum_{s=1}^{S} H_s^l \lambda_s \leq \sum_{c=1}^{C} \tilde{x}(l,c), \forall \text{ links } l \tag{3.5}$$

$$\sum_{k \in I_l} \frac{\tilde{x}(k,c)}{r(k,c)} \leq \kappa \tag{3.6}$$

$$\sum_{k \in E(i)} \sum_{c=1}^{C} \frac{\tilde{x}(k,c)}{r(k,c)} \leq \alpha(i) \tag{3.7}$$

These 3 equations come from the long term average service $\tilde{x}(l, c)$ that a link $l$ can receive on channel $c$ under the stability requirement (3.5), interference constraint (3.6) and constraint on the number of radios (3.7). Using the same Lyapunov function and the techniques outlined in [LR07], we observe that the results follow as in [LR07].

We also observe that the proven efficiency ratio of the proposed DSSO algorithm is by definition less than the frequency ratio of the DMS algorithm, that is due to the fact that the switching delay has not been taken into account in case of the optimal algorithm. In fact, when we do compare the simulation results of DSSO and DMS algorithms, it is clear that DSSO algorithm outperforms DMS significantly.

## 3.4 Simulation Results

In this section, we use simulation to evaluate the performance of the channel assignment algorithms. We first compare their system throughput and end-to-end delay with varying switching overhead $\delta$. Then we show the average backlog under different packet arrival rate.

### 3.4.1 Simulation Scenarios

We consider two different network scenarios under 2-hop interference models. In the first scenario, we consider an $8 \times 8$ grid topology where each node could potentially communicate with up to four neighbors. Schedule occurs at every time-slot during simulation time (1000 time-slots). To consider the switching delay, each time-slot is divided into ten mini-time-slots (total of 10000 mini-time-slots). The number of radios on each node varies from $2$ to $4$, which includes one default radio to maintain the topology. We assume each radio has 7 non-overlapping channels, of which one of those channels is used as the default for the default radio. We randomly selected capacity for each channel for each link from [10, 14] (uniformly distributed), which means the number of unit packet per mini-time-slot. Then we randomly pick fifteen source-destination pairs for each of the packet arrival rate $\lambda$ which follows the Poisson distribution.

For the second scenario, we consider 5 randomly generated mesh networks with 25 nodes in a square of $300 \times 300$ meters. Two nodes are connected by a link if they are within transmission range (100 meters). Each node has $4$ radios and each radio has 7 channels which has a capacity between [10, 14] (uniformly distributed). Then we randomly pick ten source-destination pairs having 5 hops each. We assume a Poisson process with packet

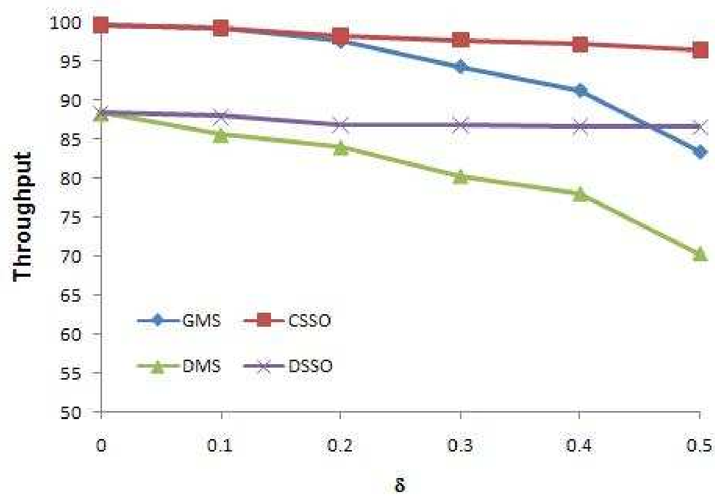



Figure 3.2: The average throughput of scheduling algorithms

generation rate $\lambda = 3$ for packet arrivals. During simulation time (1000 time-slots), the routing table is fixed. Any routing algorithm can be used to create the routing table. Our work focuses on the channel assignment and scheduling aspect only.

### 3.4.2 Simulation Results

Table 3.1: Average Backlog Improvement: Centralized Algorithm

| Network | $\delta = 0.2$ | $\delta = 0.3$ | $\delta = 0.4$ |
|---|---|---|---|
| 1 | 23.71 | 63.12 | 76.17 |
| 2 | 19.26 | 54.63 | 73.44 |
| 3 | 23.02 | 40.55 | 53.17 |
| 4 | 20.04 | 59.76 | 74.99 |
| 5 | 29.25 | 49.68 | 63.23 |

In the first scenario, we show the average backlog packets under different scheduling algorithm and switching overhead pairs. And we also show the system throughput and end-to-end delay with varying switching overhead with $\lambda = 2$. Fig. 3.2 compares the

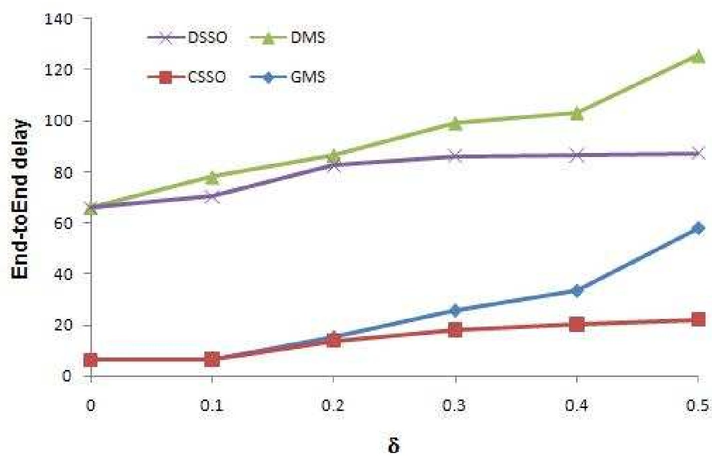



Figure 3.3: The average end-to-end delay of scheduling algorithms

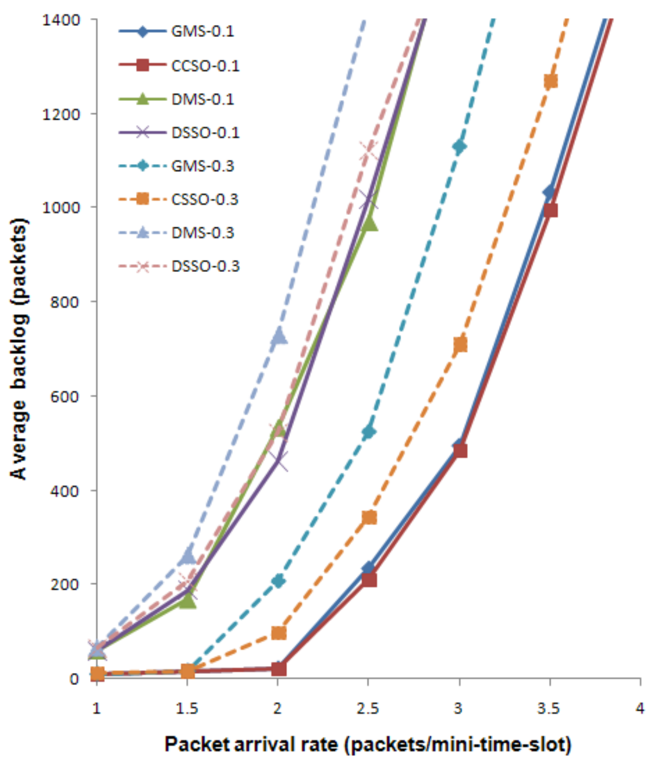



Figure 3.4: The average backlog with $\delta = 0.1$and $0.3$

Table 3.2: Average Backlog Improvement: Distributed Algorithm

| Network | $\delta = 0.2$ | $\delta = 0.3$ | $\delta = 0.4$ |
|---|---|---|---|
| 1 | 8.68 | 30.88 | 46.78 |
| 2 | 4.19 | 26.31 | 41.87 |
| 3 | 7.84 | 24.68 | 41.24 |
| 4 | 11.16 | 28.16 | 48.64 |
| 5 | 7.29 | 20.15 | 33.98 |

Table 3.3: Throughput Improvement-Centralized Algorithm

| Network | $\delta = 0.2$ | $\delta = 0.3$ | $\delta = 0.4$ |
|---|---|---|---|
| 1 | 100.94 | 110.76 | 126.97 |
| 2 | 100.78 | 110.70 | 133.50 |
| 3 | 107.52 | 124.75 | 154.34 |
| 4 | 101.45 | 111.83 | 134.61 |
| 5 | 105.05 | 119.09 | 146.88 |

throughput for different algorithms varying switching overhead $\delta$. We define the throughput as the ratio of the total received packets to the total sent packets. As shown in Fig. 3.2, the throughput of GMS and DMS which implemented without considering switching overhead has decreased dramatically when $\delta$ is larger than $0.2$ and $0.1$ respectively. However proposed algorithms (CSSO and DSSO) have almost the same performance with varying $\delta$. Fig. 3.3 presents the end-to-end delay (time-slots) with varying $\delta$ switching overhead. As expected proposed algorithms show a vast improvement over GMS and DMS.

Fig. 3.4 plots the average backlog (queue length) versus the packet arrival rate under four different scheduling algorithms with $\delta = 0.1$ and $0.3$. When the packet arrival rate (packets/mini-time-slot) approaches a certain limit, the average backlog increase dramatically. When $\delta = 0.1$, newly proposed algorithms have a slightly improved performance than others. However, when $\delta = 0.3$, the throughput performance of proposed algorithms is significantly improved. For example, GMS has more than double of the

Table 3.4: Throughput Improvement-Distributed Algorithm

| Network | $\delta = 0.2$ | $\delta = 0.3$ | $\delta = 0.4$ |
|---|---|---|---|
| 1 | 102.70 | 115.40 | 132.98 |
| 2 | 101.88 | 114.82 | 135.56 |
| 3 | 106.74 | 130.72 | 175.19 |
| 4 | 104.30 | 117.92 | 145.79 |
| 5 | 104.31 | 119.51 | 146.32 |

average backlog than our CSSO when the packet arrival rate is 2. Thus, by considering switching overhead, we can significantly improve network throughput and capacity.

In the second scenario, we considered 5 different random topologies. Table 3.1 and 3.2 show average backlog improvement of different $\delta$ values in each network. The average backlog improvement is defined as $\frac{ExistingAlgo\_backlog - ProposedAlgo\_backlog}{ExistingAlgo\_backlog} \times 100$, where $ExistingAlgo\_backlog$ is the average backlog of GMS and DMS and $ProposedAlgo\_backlog$ is the average backlog of the proposed algorithms (CSSO and DSSO). Overall, the proposed algorithms outperform in every case consistently with improvements from $7\%$ to $70\%$.

Table 3.3 and 3.4 show the improvement of throughput with varying $\delta$ in each network. The proposed algorithms can achieve up to $146\%$ of throughput improvement. By presenting the results in 5 different random topologies, we showed that our proposed algorithms always outperform the existing algorithms and the improvements become more pronounced as the switching overhead increase.

# Chapter 4

# Distributed Query Processing using Event Signatures in HWSNs

In this chapter, we consider highly resource-constrained Heterogeneous Wireless Sensor Networks (HWSNs). Two event detection protocols are proposed in Section 4.2 and Section 4.3.

## 4.1 System Model and Problem Formulation

### 4.1.1 Area as a Grid

We model the area that we would like to monitor as a grid of cells. Each cell encompasses a contiguous subsection of the area, every point in the area belongs to exactly one cell. We assume that sensor nodes are deployed throughout the area, and may be located anywhere within the grid. We also assume that each cell is monitored sufficiently by sensors to allow

Figure 4.1: Grid representing battleground with deployed sensors

for event detection.

### 4.1.2 Sensor Nodes

We assume that each node deployed in our grid is equipped with specific sensor capabilities. In our work, we assume that each node is "homogeneous," having a single sensing capability, as in [AGZAKMP10]. Each type of sensor has a particular radius of detection. We also assume that each node has a particular radius of communication determined by the broadcasting power of the node. When the sensing radii of two sensor nodes overlaps, both nodes can capture data on events that occur in the overlapping area. More formally, each sensor node $v_i$ is associated with the following information:

- location: the location within the area grid.
- detection capability: the sensor type located at the node.
- detection radii: the radii within which each sensor can detect data. For example, a temperature sensor is likely to have a much smaller radius of detection than a camera, since temperature is very localized whereas a picture can encapsulate data over a larger area.
- communication radius: the radius within which each sensor can broadcast data.

We assume that sensor nodes only capture data when they are triggered by a relevant stimulus. For example, a motion detector will only capture data when movement is observed within a certain proximity.

### 4.1.3 Cell Status as a Sensory Signature

The status of each cell in the grid is modeled by a "sensory signature" of bits, similar to the event hierarchy paradigm presented in [LLS$^+$04]. Each bit indicates the data that sensors have gathered about a specific sensory property. For example, the first bit might indicate the presence of smoke.

Each type of battle event corresponds to a signature. These bits are relevant because the value of these bits determine whether or not the event has been perceived. For example, the bits in a sensory signature that corresponds to the explosion of a bomb might indicate the presence of smoke and noise above a particular decibel.

The bits in a sensory signature can take one of the following four values: Y, N, X, and ?. "Y" means that data has been collected indicating that the corresponding property is present. Conversely, “N” means that data has been collected indicating that the corresponding property is not present. “X” means that contradictory data has been collected, some of which indicate that the corresponding property is present and some of which indicate that the property is not present. Finally, “?” means that no data has yet been collected.

**Caveat on the use of signature:** While our idea of using signature bits is quite effective, and saves significant amounts of transmission power, it suffers from one drawback - we cannot distinguish between two sets of events in the same battle cell, if the two sets of events lead to the same composite signature. As an example, consider one set of two events with bit signatures “???YYY” and “YYY???”, and another set with a single event with individual bit signature “YYYYYY”. Both of these sets are recognized as a single compound event with bit signature “YYYYYY” using our signature based protocols. This drawback is not a limitation in the business problem being considered as multiple events are also of significant interest to a battlefield commander. However, we recognize that such signature based protocols may not be applicable in all scenarios.

### 4.1.4 Query Protocol

We assume that all event queries originate from a centralized headquarters node. This headquarters “asks” the network to look out for the occurrence of a particular event by specifying the corresponding sensory signature. For example, suppose the headquarters wishes to know if a bomb has exploded in the network area, and an explosion is characterized by smoke, noise above a particular decibel, and a flash of light. The headquarters specifies a signature with three bits set indicating sufficient presence of smoke, noise, and light, respectively. It then sends its query out to the network. Sensor nodes continue to monitor the landscape until a new query is received from the headquarters.

### 4.1.5 Problem Formulation

*Given:*

- an area grid with a set of sensor nodes $\{v_1, ..., v_n\}$
- set of filters $k$, where each sensor node can have one of these $k$ filters
- the query signature of $k$ 0/1 bits which corresponds to significant event
- the maximum latency for an event detection

*Find:* all events in the area grid that satisfy the sensory signature of the significant event within the maximum latency time. As we discuss in later sections, the event query and the latency can change dynamically at the discretion of the headquarters node.

### 4.1.6 Cost Model

We assume that the sensor nodes are equipped with the capacity to filter the data they collect. More specifically, a filter takes the data that has been captured in its original form, and converts it to a true or false value based on a test. For example, a filter for pictures of smoke would reduce a picture of the ashy air around a burning building to a true value, and a picture of a river to a false value. These true and false values correspond to the "Y" and "N" values that can be placed in the sensory signature.

The performance of these filters is one factor that impacts the total cost of query processing in the network. So to evaluate the cost of our proposed solutions, we define the following terms:

- **filter cost** $c_i$: the computation cost of executing filter $F_i$. We normalize these costs to account for differences in the nodes' total power by dividing the computational power required to run the filter by the total power of the node to find $c_i$. We expect some filters to have a higher computation cost than others, depending on the complexity of the captured data. For example, a filter acting on a picture will typically be more expensive than another acting on a temperature reading.

- **filter selectivity** $s_i$: the fraction of sensory data that can be expected to pass the criteria of filter $F_i$ [SMW05]. For example, if we expect $2$ out of $10$ sound readings to measure sounds above $60$ dB, a filter for sounds above $60$ dB will have a selectivity of $20\%$. We assume that filters are independent, so that the selectivity of any given filter is not affected by the prior execution of other filters.

- **global broadcasting cost** $B_G$: the cost of broadcasting data records to all other nodes in the network. We assume a standard broadcasting protocol, where the time and cost of transmitting data throughout the network is a function of the network.

## 4.2 Distributed Query Processing using Signatures

To improve overall network performance, we would like to discard data that is determined to be irrelevant to avoid unnecessary broadcasting and processing. However, it is difficult to ensure that we can discard data safely. If the detection radius of a node is larger than its communication radius, it may be able to detect events that are within the detection radius of another node, and still have no direct communication with that node. The data must be sent through intermediate nodes in this case.

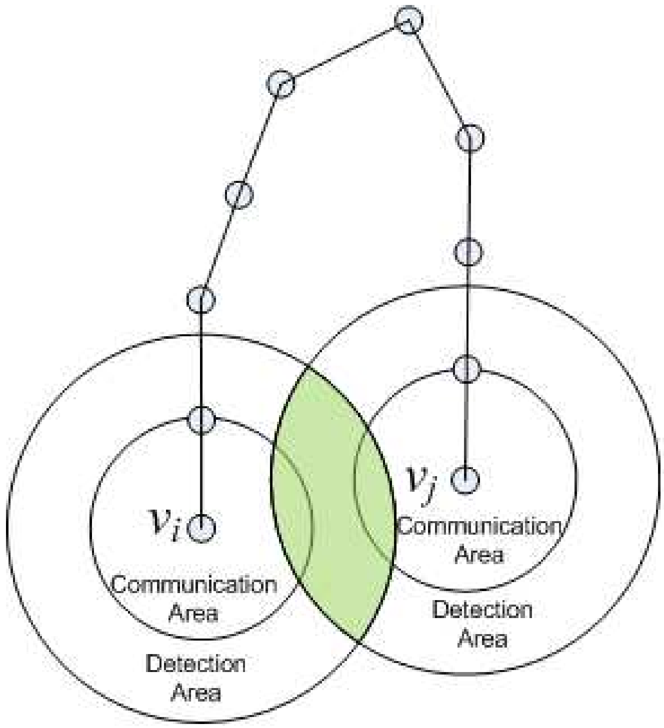



Figure 4.2: Overlapping detection areas without communication

Figure 4.2 provides an example of a network where nodes $v_i$ and $v_j$ have overlapping detection areas. As a result of this overlap, data that originates at $v_i$ might be relevant to data that originates at $v_j$, and vice versa. Intermediary nodes on the path from $v_i$ to $v_j$ might be tempted to discard data that has no relevance to the intermediary nodes, as the data is sent to nodes even further from the site of detection. However, as we observe, this data cannot be discarded safely, as it is relevant to data gathered at $v_j$.

We also must address the problem of updating the sensory signature of a cell to incorporate data gathered by several sensor nodes. Given two input signatures, we combine each bit using the $\oplus$ operator, defined as follows:

Table 4.1: Combining bits in sensory signatures

| $\oplus$ | Y | N | ? | X |
|---|---|---|---|---|
| Y | Y | X | Y | X |
| N | X | N | N | X |
| ? | Y | N | ? | X |
| X | X | X | X | X |

In addition to handling the "joining" of two individual signatures, we must also handle joining streams of sensory signatures. When sensory nodes gather data, the time of data collection is recorded. To facilitate keeping track of the time and location of data collection, we define a data structure, which is a tuple consisting of the following information: $\ll timestamp, location, sensory\ signature \gg$.

A primary advantage of using such a data structure is the pairing of time with the gathered sensory data. In order to detect an event, we would intuitively like to consolidate records with the same time and location that provide data gathered at different nodes. However, we note that it can be difficult to pair sensory data with the appropriate time.

One possibility is to match sensory data with the time at which the data was gathered. However, such a pairing might be rendered ineffective when we combine data gathered at different locations and by different types of sensors. For example, if one sensor node is twice as close to an event as another sensor node, the data gathered at each note will possess different time stamps, even though they correspond to the same event. This problem is further complicated by the fact that different physical properties travel at varying speeds. For example, sound waves travel more slowly than light. As a result, even when sensors at the same sensory node gather data on sound and light pertaining to the same event, the time stamps will be different.

Furthermore, because time is a continuous variable, there are an infinite number of possible time values. For example, two data records that correspond to the same event might display times $t$ and $t + \epsilon$. Yet they might not be consolidated because their times are different. One potential solution to this problem of continuity would be to create data records with only standardized times. The set of potential times would be of the form $t + a\epsilon_{time}$, where $t$ is the time when the system is put in place, $a$ is an integer from 0 to $\infty$, and $\epsilon_{time}$ is a predetermined constant specifying the interval between consecutive potential times. Then each data record would be assigned the time of form $t + a\epsilon_{time}$ that is closest to the actual detection time.

One practical solution to this problem of consolidating sensory data by time is to make use of the nodes' memory. If a node receives a sensory signature, and has its own sensory data stored in recent memory, we can assume that these pieces of data match.

### 4.2.1 Distributed Query Processing Protocol

In this subsection, we present an innovative battle event detection protocol using distributed query processing with sensory signature.

We assume that the sensor nodes are aware of the query signature that is of interest to the head quarters. The algorithm divides the filters into several phases which depend on the cost and the selectivity of various filters as well as the query signature. In each phase, only a set of filters is active. The filters belonging to the first phase are active at all times. The filters belonging to the subsequent phases are active only when an event matching the signature of the previous filters has been received. As the sensors receive the event messages from their neighbors, they consolidate and maintain a partial signature for each event received. When the partial signature of some events in their sensing radius matches the signature of the prior phases, the sensor becomes active. The sensors that have filters belonging to the first phase do not perform the consolidation and maintenance steps. The steps of the algorithm are shown in Algorithm 4.

---

**Algorithm 4** Distributed Query Processing Protocol

---

**Compute and Broadcast Step**
**for** each phase $i$ distributed with the query **do**
- Run the $i$th class of filters on data pertaining to cells with partial sensory signatures satisfying the query specifications.
- Update the partial sensory signature for the monitored cells with the filter results.
- Broadcast updated signature records to all neighbors.
- Update signature records based on received records.

**end for**
**Action Step** The headquarters node receives all complete sensory signatures satisfying the query specifications, and takes appropriate action.

---

#### 4.2.1.1 Algorithm for computing phases

In order to optimize the performance of Algorithm 4 in terms of total cost, the optimal number of phases must be found. This equates to determining the number of filter classes and which filters belong to each class. Since the central headquarter node generates event queries, it naturally follows that the headquarters should determine the grouping of filters into phases, and distribute this information along with the query.

In order to do this, we provide a dynamic programming algorithm. We first order the $n$ filters necessary to process the meaningful bits specified by the event query, so that $\{F_1, ..., F_n\}$ where $\frac{c_1}{1-s_1} \leq \frac{c_2}{1-s_2} \leq ... \leq \frac{c_n}{1-s_n}$. This ranking is derived from the work done in [SMW05]. We also define the cost function $c(F_x, F_y, k)$ to be the cost of running filters

$F_x$ through $F_y$ using at most $k$ phases.

In the following algorithm, $k^*$ is the maximum number of phases possible that satisfy the maximum allowed latency for an event detection. For example, suppose it takes $t_{broadcast}$ time to broadcast data to all nodes in the network, $t_{filters}$ time to run all filters, and we want the headquarters to be alerted about events with a maximum latency of $t_{latency}$ time. Then the maximum number of phases possible is $k^* = \lfloor \frac{t_{latency} - t_{filters}}{t_{broadcast}} \rfloor + 1$, since $(k^* - 1)t_{broadcast} + t_{filters} \leq t_{latency}$. We further observe that $k^*$ cannot exceed $k$, as there must be at least one filter in each phase.

**Algorithm 5** Dynamic Programming Algorithm to Determine the Optimal Number of Phases.

**for** $x = 1$ to $n$, and $y = x$ to $n$ **do**

  $c(F_x, F_y, 0) = \sum_{i=x}^{y} c_i$ since this is simply the sum cost of running filters $F_x$ through $F_y$.

**end for**

**for** $k_1 = 1$ to $k^*$ **do**

  **for** $x = 1$ to $n$, and $y = x$ to $n$ **do**

    $c(F_x, F_y, k_1) =$

    $$\min_{z=x}^{y} \left\{ c(F_x, F_z, k_1 - 1) + t_{broadcast} + \prod_{i=x}^{z} s_i c(F_{z+1}, F_y, 0)) \right\}$$

  **end for**

**end for**

**return** $\min_{k_1=1}^{k^*} c(F_1, F_n, k_1)$

***Time Analysis***: Algorithm 5 runs in $O(n^4 k)$ time where $n$ is the number of sensor nodes, and $k$ is the number of filter types, since the second loop runs at most $O(n^2 k)$ times, the $min$ function inside must compare at most $n$ values, and the inner product must multiply at most $n$ elements. However, we can reduce this run time to $O(n^3 k)$ by computing the possible product values $\prod_{i=x}^{z} s_i$ for all values of $x$ and $z$ in $O(n^2)$ time once before entering the loop.

## 4.3 Localized Query Processing Protocol

Depending on the landscape and sensor types, the relation between the computation cost and communication cost can be different. The Distributed Query Processing Protocol presented in Section 4.2 focuses on minimizing the computation cost. However, if the communication cost dominates computation cost, then a different approach can be helpful.

In this section, we present a leader based protocol which focuses on reduce communication cost. Each cell has a leader node that gathers the partial sensory signatures from all cell members. In this localized protocol, all filters are active at all times. When a node runs a filter, it transmits the updated records to the local leader node. Nodes receive, process and forward the event signatures based on following two rules:

- A leader node only processes information from its local nodes or other leader nodes
- Non-leader nodes do not process or forward any information.

The steps of this algorithm are shown in Algorithm 6.

## 4.4 Simulation Results

In our simulation, we deploy nodes with varying sensing capabilities and detection radii. Sensing capabilities of the nodes are coupled with filtering capabilities, which have associated costs. We assume that we have 10 basic types of data. The costs and detection

**Algorithm 6** Localized Query Processing Protocol

**Compute and Broadcast Step**

1. Nodes process events that trigger their corresponding filters.
2. Nodes transmit the event signatures to their local leader nodes.
3. Leader nodes update signature records based on received records and transmit updated signature records to the other leader nodes.

**Action Step** The headquarters node receives all complete sensory signatures satisfying the query specifications, and takes appropriate action.

radii of the corresponding filters are shown in Table 4.2. Table 4.2 provides a mapping of these capabilities to real sensor node classifications, extrapolated from the sensor capabilities presented in [AGZAKMP10]. We normalize the distribution of these sensor nodes so that the area is monitored by the same number of each type of sensor, as shown in Figure 4.3. Accordingly, the number of sensors deployed with a given detection radius is inversely proportional to the square of the radius. The communication radius of each sensor node is randomly selected from $[10, 100]$. In each simulation, we introduce $10$ events, and a random number of these $10$ have the matching event signature for our query.

Table 4.2: Sensor filter capabilities

| **Filter** | **Sample Processor** | **Cost** | **Detection Radius** |
|---|---|---|---|
| Picture (low res) | Cyclops-ATmega128L MCU+CPLD | 100 | 20 |
| Picture (high res) | MeshEye-ARM7TDMI based on ATMEL | 600 | 50 |
| Temperature | Mica2Dot-ATmega128L 4MHz | 1 | 10 |
| Light | Mica2Dot-ATmega128L 4MHz | 1 | 10 |
| Sound | FireFly-ATmega128L 8MHz | 5 | 10 |
| Motion | Imote2-PXA271 XScale 13MHz | 20 | 10 |
| Chemical (simple) | MeshEye-ARM7TDMI based on ATMEL | 600 | 50 |
| Chemical (complex) | CITRIC-Intel XScale PXA270 CPU | 3000 | 100 |
| Video (low res) | MeshEye-ARM7TDMI based on ATMEL | 600 | 50 |
| Video (high res) | CITRIC-Intel XScale PXA270 CPU | 3000 | 100 |

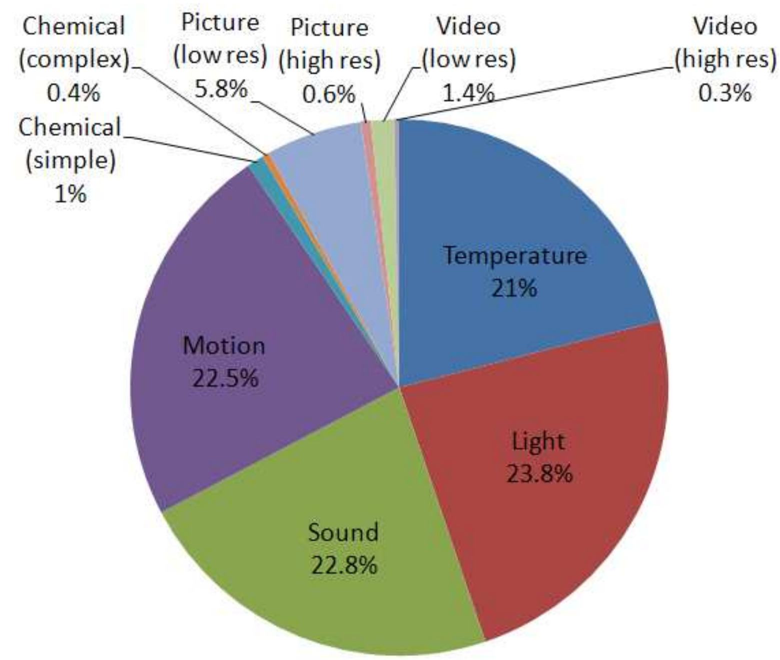



Figure 4.3: Distribution of sensors

In each of our simulations, we compare three protocols: the distributed protocol and localized protocol described in this work, as well as a naive protocol. This naive protocol consists of filtering and broadcasting all data as soon as it is gathered at the sensors. These protocols are compared in terms of cost. Since power resources are limited and crucial for sensor networks, we model our cost function to represent power. This includes computational power to run filters and gather data, and communication power to transmit and receive data.

### 4.4.1 Protocol Effects on Total Power

First, we analyzed the effect of the environment size on the total power cost of our algorithms. Figure 4.4 presents the simulation results reflecting the impact of the environment size, in terms of number of sensors, on the total cost, which includes the cost of transmission, reception, and computation. We see that both our distributed and localized protocols present significant improvements over the naive protocol. As the environment area grows, our protocols are increasingly beneficial, because they avoid processing and transmitting increasingly large amounts of data through an increasingly large area.

More specifically, the naive protocol transmits the original gathered data to the headquarters whenever that data satisfies the corresponding filter. We assume that the size of this original sensory data is proportional to the cost of the filter. Because our protocols reduce the original data to a single sensory signature, the amount of data that passes through the network is greatly reduced. Figure 4.4 demonstrates the scalability of our solutions, in comparison to the naive solution.

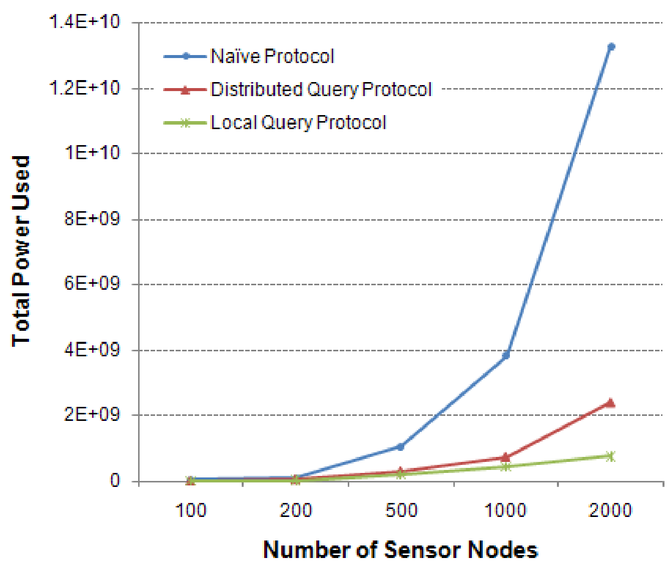



Figure 4.4: Total Power Used by 3 protocols, as a function of network size.

We note that the total power cost includes the cost of both computation and communication. Because communication costs contribute a large fraction of the total cost in sensor networks, our localized protocol outperforms the distributed protocol, since it transmits signatures to local leaders only.

### 4.4.2 Protocol Effects on Computational Power

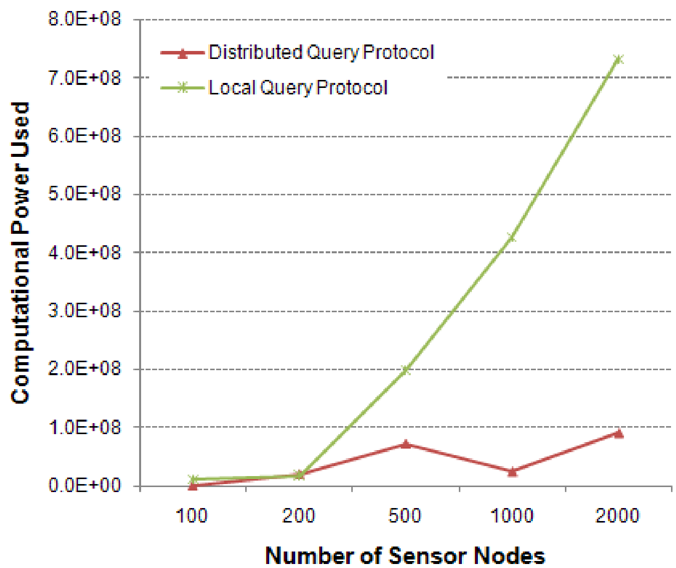



Figure 4.5: Protocol Effects on Computational Power

Finally, we explore the effect of network size on the computational power used by the sensor nodes. As the computational capabilities of sensor nodes dramatically improve, the cost of computation at sensor nodes becomes increasingly important. Therefore, we isolate and explore computational performance.

Figure 4.5 presents our simulation results, using the same simulation settings described above. As shown in the graph, our distributed query protocol reduces the consumption of computational power through its use of phases. Since our protocol runs filters in groups, only running filters assigned to later phases for potential event sites, it avoids running these filters excessively. In our simulation settings, our protocol was optimized with two phases. Our results thus demonstrate that even dividing the filters into two phases saves a considerable amount of computational power.

# Chapter 5

# Uplink Traffic Pattern in Mobile Data Network

User-generated content (UGC) also known as user-created content (UCC) refers to various kinds of media contents that are produced by end users. A recent trend in the use of the Internet exhibits that data traffic from UGC is rapidly growing with the potential to create a huge amount of uplink traffic for wireless operators [fECoO]. As the reality of UGC's scope and power is becoming crystalized (e.g., YouTube, Facebook, Wikipedia, MySpace, and Flickr), modeling and analysis of uplink traffic has just begun to receive attention in the wireless research community [PCJ+05]. As the third factor that limits network performance, we consider this new traffic pattern.

## 5.1 Traffic Measurement and Self-Similarity Analysis

Recent empirical studies of traffic measurements from a variety of different packet networks have demonstrated that the self-similarity or burstiness over a wide range of time scales is a prevalent phenomenon [LTWW94][CB96][JNHT01]. Most of network traffic measurements have been performed on wired networks with some performed on wireless downlink data networks. Little attention has been paid to uplink traffic until recently. We were only able to find one report [PCJ$^+$05] in the literature that deals with real uplink traffic obtained from WAP services in a CDMA1x network. As a growing number of end users are embracing the full potential of mobile technologies to create and share multimedia contents, most of wireless mobile operators are providing multimedia services commonly called multimedia messaging (MMS) services to support uploading of multimedia files such as pictures, video files, and music files. We have analyzed live traffic traces of MMS services collected from WCDMA networks of SK Telecom.

Currently SK Telecom has over 1,000 base stations for each network, two Serving GPRS Supporting Nodes (SGSNs) covering WCDMA networks and two Packet Data Serving Nodes (PSDNs) serving CDMA networks. Two traffic collectors are located at one SGSN and one PDSN, respectively. MMS traffic data were collected from WCDMA network for every 24 hours from August 10 to 15, 2007. In the following, we proceed to discuss the self-similarity and our analysis of this traffic trace.

There are many different definitions of self-similarity. One common definition is for continuous time processes, which states that $Y(t)$ is self-similar with self-similarity parameter $H$ $(0 < H < 1)$ if for all $a > 0$ and $t \geq 0$,

$$Y(t) =_d a^{-H} Y(at) \tag{5.1}$$

where the equality is in the sense of finite dimensional distributions. A canonical example of such a self-similar process is fractional Brownian motion. But we need a definition that is more applicable to analyzing network traffic traces to estimate the self-similarity parameter or the Hurst parameter $H$.

Let $X(t), t \in \mathbb{Z}$ be a covariance stationary stochastic process with autocorrelation function $r(k)$. Define the aggregated process $X^{(m)}$ of $X$ at aggregation level $m$ by averaging the original process $X$ over a non-overlapping blocks of size $m$. Let $r^{(m)}(k)$ denote the autocorrelation function of $X^{(m)}$. The following is a definition of self-similarity for discrete time stochastic process.

**Definition 1.** $X(t)$ is exactly second-order self-similar with Hurst parameter $(1/2 < H < 1)$ if

$$r(k) = r^{(m)}(k) = \frac{1}{2}((k+1)^{2H} - 2k^{2H} + (k-1)^{2H})$$

for $k \geq 1$. $X(t)$ is asymptocally second-order self-similar if

$$\lim_{m \to \infty} r^{(m)}(k) = \frac{1}{2}((k+1)^{2H} - 2k^{2H} + (k-1)^{2H}).$$

The self-similar processes can be characterized by (i) the variance of the sample mean that decreases more slowly than the rate $m^{-\beta}$, i.e., var$(X^{(m)}) \sim c_1 m^{2H-2}$ for $1/2 < H < 1$, (ii) the autocorrelation function $r(k)$ that asymptotically behaves like $c_2 k^{2H-2}$ for $1/2 <$

$H < 1$, and thus $\sum_k r(k) = \infty$ (long range dependence), and (iii) the spectral density $f(\cdot)$ that obeys a power law near the origin, i.e., $f(\lambda) \sim c_3 \lambda^{1-2H}$ for $1/2 < H < 1$.

These properties of self-similar processes lead to various methods for estimating the Hurst parameter $H$ (see [Pop91]). We estimated the Hurst parameter for MMS traffic using an analysis tool SELFIS [Kar02]. Table 5.1 shows the results for estimated Hurst values obtained using six different methods: Aggregate variance,R/S, Periodogram, Absolute moment, Whittle estimator, and Abry-Veitch. The results demonstrate that the Hurst values are between 0.5 and 1 indicating the self-similarity.

Table 5.1: Hurst Parameter

| **Estimation method** | **MMS (Hurst parameter)** |
|---|---|
| Aggregate variance | 0.920 |
| R/S | 0.739 |
| Periodogram | 0.785 |
| Absolute moment | 0.766 |
| Whittle estimator | 0.845 |
| Abry-veitch estimator | 0.745 |

### 5.1.1 Heavy-tailedness

The heavy-tailedness is roughly said to cause a network traffic to possess the self-similar property. A random variable $Z$ is said to obey a heavy-tailed distribution if

$$P(Z > x) \sim cx^{-\alpha}, \quad x \to \infty \tag{5.2}$$

where $0 < \alpha < 2$ is the tail index and $c$ is a positive constant. The variable $Z$ could represent a session size, or inter-session time between two successive sessions. In order to check for the heavy-tailedness of the distribution of a given variable, we make use of

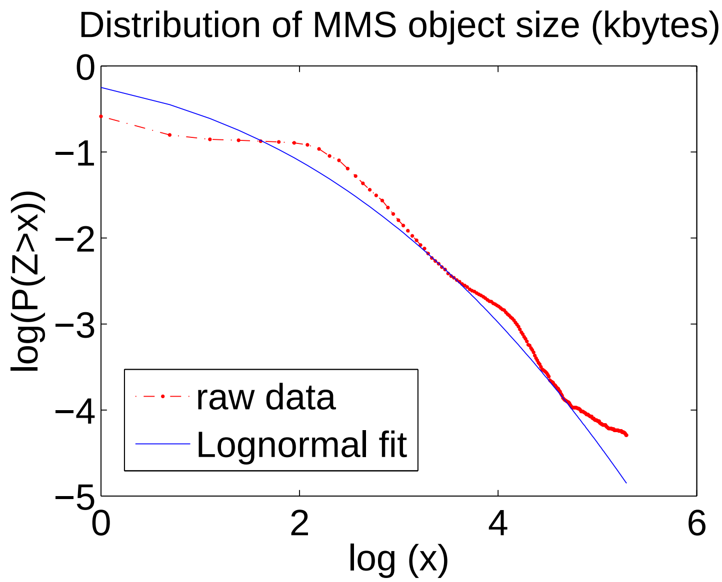



Figure 5.1: Log-log plot of MMS object size

complementary distribution plots. Indeed, if we take logarithms of both sides of Eq. (5.2), we obtain

$$\log(P(Z > x)) \sim -\alpha \log(x) + \log(c), \quad x \to \infty.$$

This relation says that if a variable obeyed the heavy-tailed distribution, the log-log plot of the complementary distribution of the variable would be a straight line for large $x$-values, with a slope $-\alpha$.

In Fig. 5.1, we show the log-log plot of the complementary distribution of the MMS raw data. This figure suggests a strong empirical evidence of the heavy-tailed property of the file size distribution for MMS services.

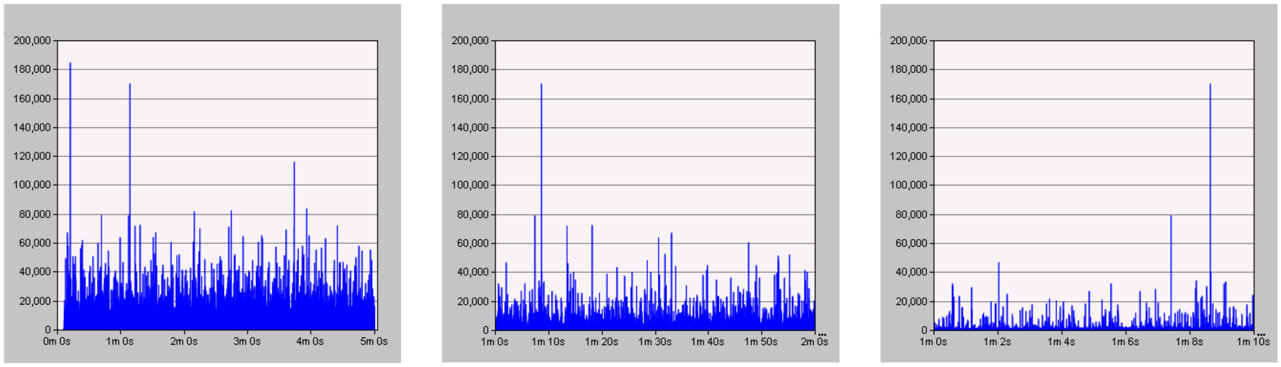
## 5.2 Impact on Network Performance

In this section, we analyze the impact of uplink traffic characteristics on the network performance using the WiMAX module available by OPNET 12.0 developed based on IEEE 802.16e. In our simulations, we use the MMS uplink traces collected from the SK Telecom network to model best-effort multi-media uplink traffic. Video-telephony traffic modeled in OPNET 12.0 is used to model delay-sensitive uplink traffic. The topology of a simple network is used where subscriber stations are connected to a single base station. We only model the wireless connection between BS and SSs, i.e., the radio layer in the access network, and a round-robin scheduling QoS algorithm for WiMAX available in the OPNET 12.0 is applied. The round-robin WiMAX QoS scheduling algorithm implemented in OPNET is briefly described next.

The latest IEEE 802.16e supports five scheduling service types:

- Unsolicited Grant Service ($UGS$)
- Extended Real-time Polling Service ($ertPS$)
- Real-time Polling Service ($rtPS$)
- Non Real-time Polling Service ($nrtPS$)
- Best Effort ($BE$)

$UGS$ and $ertPS$ have the highest scheduling priority, and packets from SSs with these services are periodically inform their queue status information to the scheduler which resides in the base station. $rtPS$ and $nrtPS$ have the middle priority, and packets from SSs with these services are scheduled for transmission after clearing packets in the buffer with




(a) 300s period (b) 60s period (c) 10s period

Figure 5.2: Aggregate traffic with 64 MMS and 64 video-telephny services

$UGS$ and $ertPS$ services. $BE$ has the lowest priority and all connections from SSs share a same scheduling queue by first-come-first-served. In our simulations, video-telephony is categorized as $rtPS$, and $MMS$ is categorized as BE, and only traffic video-telephony services is considered delay-sensitive.

### 5.2.1 Delay Analysis with Low Load Delay-Sensitive Traffic

We first consider a scenario in which both MMS and video-telephony traffic loads are low. The parameters used for traffic generation are summarized in Table 5.2.

Table 5.2: Summary of parameters

| **Parameters** | **Values** |
|---|---|
| Simulation Time | 300 seconds |
| Number of video-telephony SS | 64 |
| Number of MMS SS | 64 |
| video-telephony packet size (bytes) | Lognormal(6.0, 1.0) |
| video-telephony packet interarrival time (seconds) | Constant(0.1) |
| MMS packet size (kbytes) | Lognormal(1.2, 1.5) |
| MMS packet interarrival time (seconds) | Exponential(2.88) |

Figure 5.2 (a) shows the total amount of aggregate traffic (in bytes/sec), over the entire simulation time, received at the server. This figure is then zoomed into $60$ seconds (b) and $10$ seconds (c) of simulation periods. The traffic burstiness is observed across all time scales. This scale-invariant burstiness shows the self-similarity property. Similar results are also discovered for MMS traffic and video-telephony traffic at each SS.

Since video-telephony is delay-sensitive, a major QoS requirement should be the delay. We assume that the delay requirement for this service is to have at least $99\%$ of packets experience delays less than $0.03$ seconds, and services meeting this requirement are considered satisfiable.

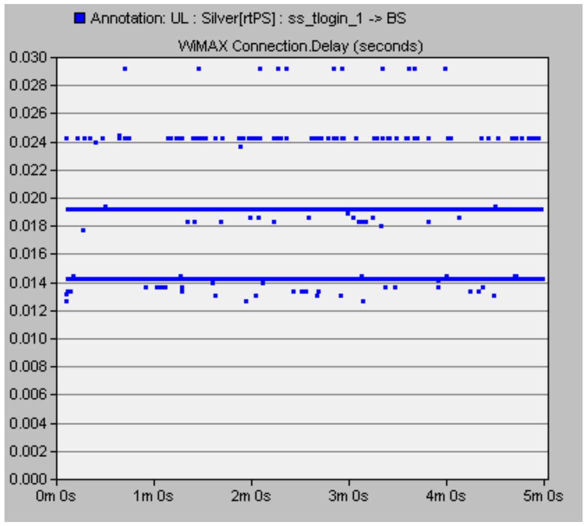
Packet delays of video-telephony service at a single SS is shown in Fig. 5.3(a). The QoS requirement of the video-telephony is fulfilled as shown, and it can be also clearly verified by the cumulative density function CDF of the delay shown in Fig. 5.3(b).

### 5.2.2 Delay Analysis with High Load Delay-Sensitive Traffic

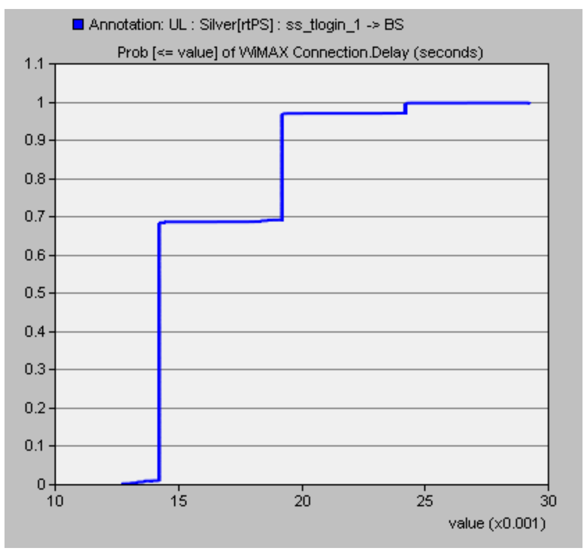
In this scenario, we increase the traffic loads from both MMS and video-telephony services by injecting $108$ SSs with MMS services and $108$ SSs with video-telephony services.

The aggregate traffic received at the BS is shown in Figure 5.4. We note here that the burstiness is also observed and the total traffic received at the BS (in the range of $40$ to $60$ bytes/sec) is much lower than the network capacity (theoretical max capacity of WiMAX is $70$ Mbps).

As the total number of SSs is increased to have $108$ MMS SSs and $108$ video-telephony SSs, the delay of video-telephony packets is largely affected even though they are served under the rtPS category with the higher scheduling priority. From the Fig.5.5(a), it is clear that the delays are much larger in this case than those in the previous scenario with $64$ MMS SSs and $64$ video-telephony SSs. A closer look at the CDF plot of the packet delay shown in Figigure 5.5(b) reveals that at least $5\%$ packets have delays larger than $0.03$ seconds. Here we should note that the aggregated traffic load in any moment is much less than $250$ kbytes, which is far less than the network capacity. This observation depicts that the network resource has not been fully utilized. Better scheduling algorithms and access control schemes should be developed to improve the network's performance in supporting QoS requirements.




(a) Packet delay




(b) CDF of packet delay

Figure 5.3: Packet delay of video-telephony with $64$ MMS and $64$ video-telephony SS

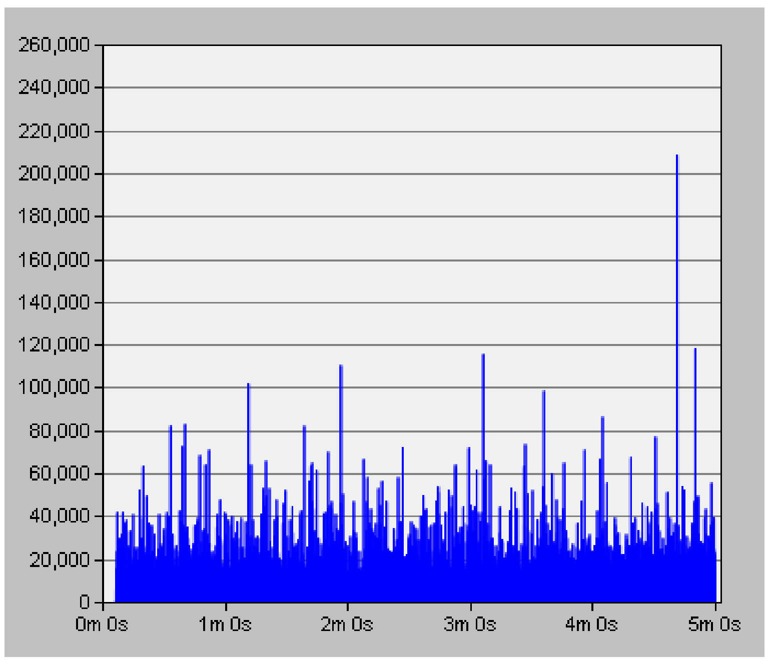
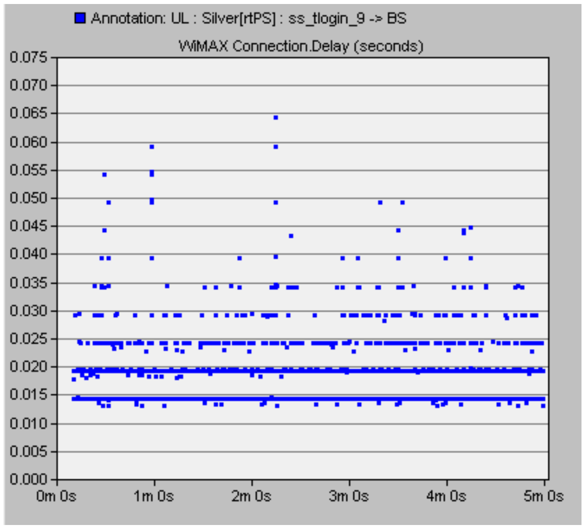
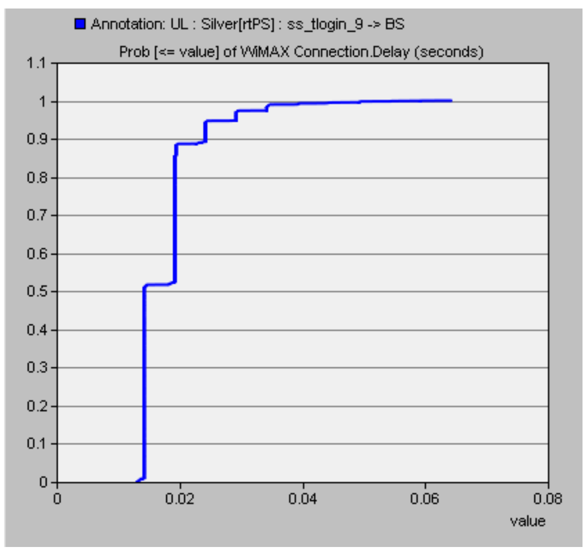



Figure 5.4: Aggregate traffic with 108 MMS and 108 video-conferencing.




(a) Packet delay




(b) CDF of packet delay

Figure 5.5: Packet delay of video-telephony with $108$ MMS and $108$ video-telephony SS

# Chapter 6

# Conclusion and Future Directions

This dissertation research investigated major factors that limit network throughput and capacity, and developed new schemes with aforementioned factors explicitly considered in heterogeneous wireless networks.

## 6.1 Contributions

The contributions of this dissertation are in three different areas: resource sharing in HWMNs, information processing in HWSNs, and new traffic pattern in 3G/4G networks.

### 6.1.1 Channel Assignment considering Switching Overhead in HWMNs

1. The switching overhead that is incurred during channel switching is explicitly modeled, and channel assignment algorithms are designed by using that delay.

2. We showed that the well known GMS dose not achieve any provable efficiency ratio

when the switching overhead is considered.

3. We extended two well known algorithms, centralized and distributed, taking the switching overhead into account in the channel assignment.

4. Performance of the developed algorithms is analyzed through discrete-event simulations.

### 6.1.2 Distributed Query Processing using Event Signatures in HWSNs

1. The problem of identifying significant events is addressed with the objective of minimizing the total power cost in HWSNs.

2. We proposed two protocols that can reduce the computation cost and the communication cost for the sensor network, thereby extending the life of the network. The suggested protocols employ three main techniques to reduce these costs:

   (i) use of sensory signature to avoid sending raw or processed data

   (ii) use of phases to avoid unnecessary computations

   (iii) use of leader nodes to avoid unnecessary communications.

3. Performance of the developed protocols is analyzed through discrete-event simulations.

### 6.1.3 Uplink Traffic Pattern in Mobile Data Network

1. We analyzed live uplink traffic traces obtained by monitoring 3G networks of a mobile data service provider (SK Telecom in Korea).

2. Our statistical analysis showed the self-similarity in this traffic trace. Six different self-similarity analysis algorithms are used.

3. The impact of this traffic characteristics on mobile data networks is evaluated through the WiMAX module available in OPNET software.

## 6.2 Future Directions

Our research can be further extended in the following avenues:

1. **Switching Overhead:** Current switching overhead $\delta$ model does not include switching type information. As mentioned in Section 3.1.2, when switching occurs across different frequency bands (e.g., 5GHz for 802.11a and 2.4GHz for 802.11b/g), the impact of switching delay on the overall network performance becomes even more significant. Thus, radio switching across different frequency bands can be modeled separately from in-band channel switching.

2. **Event Detection:** In addition to the single type of event detection, further research can consist of using sensor network to detect multiple types of events simultaneously. For example, we may want to detect bomb explosions, gunfire and chemical agent deployment simultaneously. Future work can also consist of combining the helpful attributes of the two protocols suggested in this research. Distributed query processing protocol reduces computation cost, and localized query processing protocol reduces communication cost. A protocol that combines aspects of these two protocols could possibly reduce both, and still detect events correctly.

3. **Traffic Pattern:** Our observation suggests that call admission control should be carefully monitored for delay-sensitive uplink services as most of admission control algorithms only focus on the available network capacity. Further research on developing uplink scheduling algorithms integrated with call admission control is also required to deal with the new uplink traffic patterns.

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