WIRELESS NETWORKS: OPPORTUNITIES FOR INFRASTRUCTURE-RELATED OPTIMIZATION

Chutima Boonthum
Hampton University, Hampton, VA 23668,USA

Stephan Olariu, Ekaterina Shurkova, Lan Wang, and **Qingwen Xu**
Old Dominion University, Norfolk, VA 23529, USA

Keywords: Cellular Networks, Satellite Networks, Network Infrastructure, Optimization, Quality of Service, Sensor Networks, Mobile Computing.

Contents

Summary

The main contribution of this chapter was to survey a number of contemporary wireless

networks and to investigate ways in which resource optimization (in a broad sense) is practiced and implemented in these networks. The chapter should be of interest to IT practitioners and engineers. It was written with the non-expert in mind. We have to make painful compromises: instead of sophistication of presentation we have settled for clarity of exposition. We trust that the chapter will appeal to a broad readership.

1. Introduction

In the past decade, the areas of mobile computing and wireless networks have seen an explosive growth both in terms of the number of services provided and the types of technologies that have become available. Unlike their wired counterparts, most types of wireless networks are rapidly deployable, scale well, and are cost-effective. For example, it is increasingly clear that the use of e-commerce is becoming an important new tool for the manufacturing and retail industries and an imperative new development for all industries striving to maintain a competitive edge. Companies can use the mechanisms and technologies offered by e-commerce to put their stores on-line. At the same time, customer mobility has emerged an important catalyst triggering a new paradigm shift that is redefining the way we conduct business. An important feature of mobile commerce is that the on-line store is accessible 24 hours per day to a potentially huge customer base scattered around the world (Barnes and Huff, 2003; Jamalipour and Tung, 2001; Luglio, 1999; Olariu et al., 2003; Olariu, 2005). By their very nature, mobile commerce applications will rely increasingly on wireless communications. To be cost effective and, thus economically viable, these applications will have to reach a wide consumer base. In turn, this suggests that a wide coverage — indeed, a global one — is a must in mobile commerce. As illustrated in Figure 1, such a global coverage can only be achieved by a combination of terrestrial and satellite networks.

The widening availability of mobile information systems is being driven by the increasing demand to have information available for users at any time. As the availability of wireless devices increases, so will the load on available radio frequency resources. We are witnessing an unprecedented demand for wireless networks to support both data and real-time multimedia traffic. While best-effort service suffices for datagram traffic, the usability of real-time multimedia applications is vastly improved if the underlying network can provide adequate Quality-of-Service (QoS) guarantees.

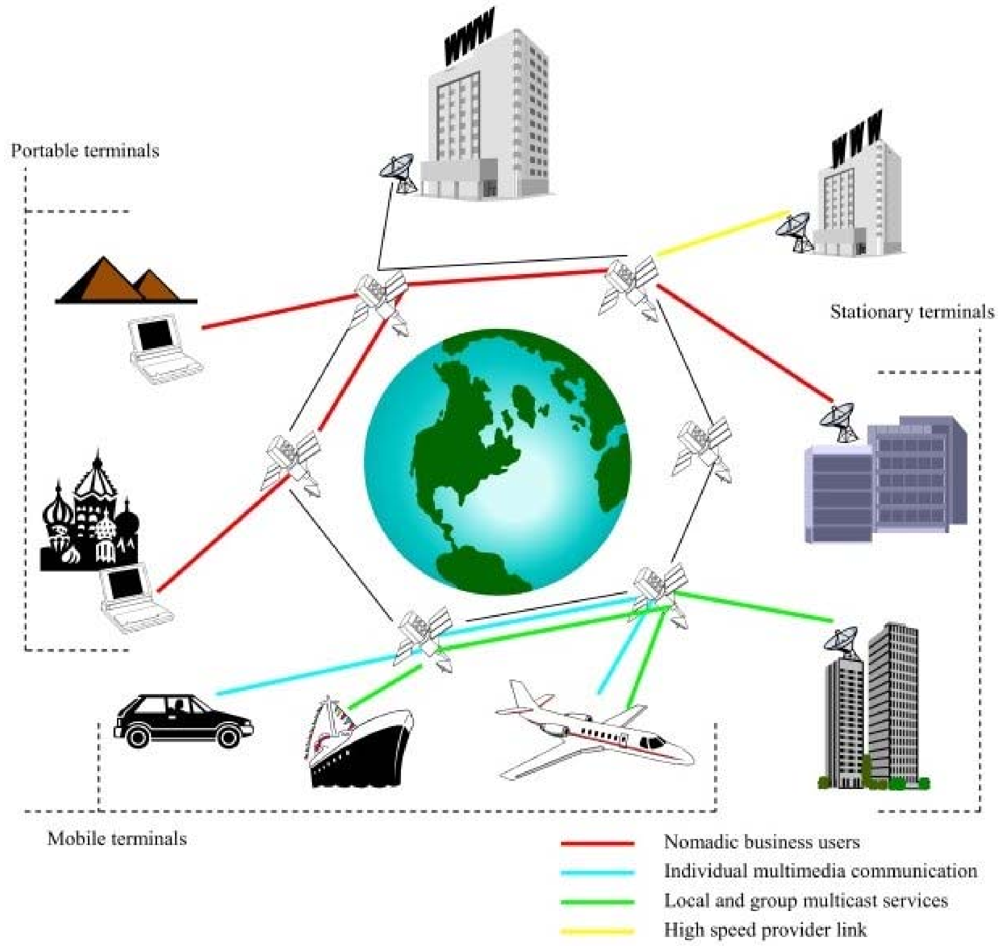

Figure 1: An integrated terrestrial and LEO satellite system

Given its importance, QoS provisioning for wireless networks is an active area of research with myriads of papers being published each year. Historically, QoS provisioning in wireless networks started with the well-known cellular networks. Cellular phones are now ubiquitous all over the world. Because the physical infrastructure costs of wireless networks are so much less expensive than those of wired networks, in many developing countries, the wireless coverage, in area and population, is greater than the wired coverage. With the increased number of users, there is a growing demand for more services. Users want to access services that are being routinely offered by wired networks, including email, instant messaging, web browsing, and even video streaming and video conferencing, as well as the more common services like telephony and paging, from anywhere or while on the move.

Many cellular network providers in the U.S. and abroad can provide users access to telephony, paging, instant messaging, and trivial web browsing on the same device. Some new phones add the ability to do more complex web browsing by combining a small PDA with a phone handset. And users that have more powerful computers equipped with wireless network access want to be able to use the same, possibly high-bandwidth, applications they are accustomed to using with wired network access, such as video conferencing and other real-time networked applications.

QoS provisioning in single-class traffic wireless networks is a more complicated task than it is for wired networks due to physical constraints, bandwidth constraints and user mobility. Clearly, providing QoS guarantees to users of wireless networks that handle different types or classes of service is an even more complex task, and it is currently a busy research area.

Some well-known QoS measures, such as delay, bandwidth, jitter and error rate, are important in both wired and wireless networks. In the context of wireless networks an important QoS parameter is the *call blocking probability* (CBP), denoting the likelihood that a new connection request will be denied admission into the network. A similar situation arises when an established connection in one cell attempts to migrate into a neighboring cell (i.e. a handoff is attempted). If the new cell cannot support the level of resources required by the connection, the handoff is denied and the connection is dropped. The *call dropping probability* (CDP) expresses the likelihood that an existing connection will be forcibly terminated during a handoff between cells due to a lack of resources in the target cell. The CBP and CDP together offer a good indication of a network's quality of service in the face of mobility. An additional important consideration is the degree to which the network makes an effective use of bandwidth — unquestionably its scarcest resource. This parameter, referred to as *bandwidth utilization*, expresses the ratio between the amount of bandwidth used by various applications admitted into the network and either the total bandwidth requested or the total bandwidth available, whichever is smaller. Keeping both CBP and CDP low, while maximizing bandwidth utilization is one of the most challenging tasks facing protocol designers.

However, it is a well recognized fact that one of the critical aspects, indeed a prerequisite, of QoS provisioning is a judicious infrastructure that can be successfully leveraged by communication and connection admission protocols. It is widely known, but well worth recalling, that admission control and bandwidth allocation schemes can offer wired networks the ability to provide their users with such guarantees. Admission control refers to the task of deciding if a connection should be admitted into, and supported by, the network. Admission control is necessary for real-time, continuous media connections since the amount of resources requested by these connections may not match the level of resources available at the time of connection setup (Olariu et al 2005a). Admitting a connection into the network is tantamount to a contract between the network and the connection: on the one hand the network guarantees that a certain level of resources will be maintained for the duration of the connection. On the other hand, the connection is expected not to request additional resources over and above those negotiated at connection setup. The agreed-upon amount of resources that the network guarantees to a connection is commonly referred to as QoS. Traditional QoS parameters include bandwidth, end-to-end delay, and jitter. However, there are some QOS parameters that are specific to wireless networks.

Due to host mobility, scarcity of bandwidth and an assortment of channel impairments, the QoS provisioning problem is far more challenging in wireless networks than in their wired counterparts. For example, a mobile host may be admitted into the network in a cell where its needs can easily be met, but the mobile host may eventually move to a cell that has little or no resources to offer. Since user mobility patterns and the availability of resources in various cells along its future trajectory are not known in advance, global QoS guarantees are very hard to provide (El Kadi et al., 2001; Olariu et al. 2005b).

It is typical in most admission schemes to deny service to a new connection whose requests for resources cannot be met by the network. In such a case, the connection is said to be blocked. Traditional admission control protocols, that strive the minimize CDP and CBP are, in many cases, too conservative and pessimistic. Indeed, multimedia applications are known to be able to tolerate and adapt to transient fluctuations in QoS (Chen and Liestman, 2003; El-Kadi et al., 2001). This adaptation is typically achieved by the use of an adjustable-rate codec or by employing hierarchical encoding of voice and/or video streams (Olariu et al., 2003, Olariu et al 2005c). The codec, along with appropriate buffering before play-out, can allow applications to gracefully adapt to temporary bandwidth fluctuations with little or no perceived degradation in overall quality.

The graceful adaptation of applications to transient fluctuations in QoS is fundamental in wireless networks, where QoS provisioning is a very challenging task. As we shall demonstrate in this paper, the additional flexibility afforded by this ability to adapt can be exploited by protocol designers to significantly improve the overall performance of wireless systems.

As we briefly mentioned, once a connection is admitted into the network, resources must be allocated, at the negotiated level, for the duration of the connection. It is important to realize that in a cellular network where the user may move through the network traversing a sequence of cells; this commitment cannot be only local to the cell in which the connection originated. If the connection is to be maintained after the user crosses the boundary between neighboring cells (i.e. after a handoff), the network must guarantee an appropriate level of resources in each new cell that the user traverses. Without detailed knowledge about the intended destination of each connection, honoring this commitment is a very difficult task, indeed.

2. Cellular Networks -- Basics

Cellular networks usually consist of a set of base stations connected together through a wired network, and mobile hosts that communicate through their local base station to reach other mobile hosts or the wired internet. The area served by one base station is called a *cell*, and cells are commonly arrayed in a honeycomb pattern, with each cell having 6 neighbors, as illustrated in Figure 2. When a *mobile user* (user, for short) moves out of the range of one *base station* (BS) and into the area served by a neighboring base station, a *handoff* or *handover* is said to occur.

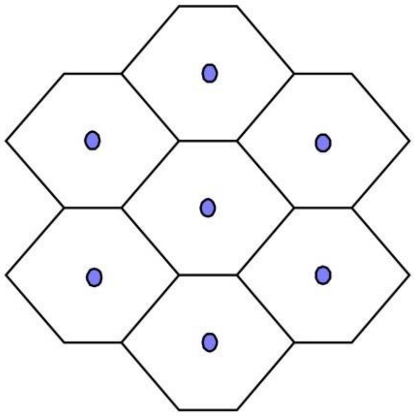

Figure 2: Illustrating a cellular system

Since this chapter does not focus on packet-level QoS, we will not review the work done in that area, but rather begin with call-level QoS and channel allocation. Because of co-channel interference, the entire frequency spectrum assigned to a network cannot be used in each and every cell.

2.1. Channel Assignment Schemes – A Quick Overview

There has been much research devoted to the problem of allocating channels to cells in order to maximize the available bandwidth for user requests. The simplest is the *fixed* channel allocation, in which all the channels of the spectrum are distributed statically to the base stations in a pattern that reduces or prevents co-channel interference. Each cell has a fixed number of channels to accommodate new and handoff calls. In *dynamic* channel assignment schemes, frequency channels are assigned to cells as they are needed. Let us note that dynamic channel assignment schemes tend to be complex and require a central controller. *Hybrid* channel assignment schemes are hybrids of fixed and dynamic assignment, where a set of channels is distributed statically and the rest of the channels are kept in a pool to be distributed as the need arises. Dynamic channel assignment outperforms fixed assignment when a few cells are highly loaded, because highly loaded fixed assignment cells will exhaust all their available bandwidth with no means to obtain more. However fixed assignment performs better under uniformly high load conditions, unless the dynamic assignment scheme can produce the optimal configuration of fixed assignment as it progresses.

Adding bandwidth to a mobile network is an expensive operation. When developing a mobile network's infrastructure, wasting bandwidth should be avoided because it is very costly. Thus, the objective is to try and get the most out of the minimum infrastructure. The same problem applies to a mobile network that is already installed, where it is cheaper to utilize the available resources more effectively than to add more bandwidth.

The channel allocation problem involves how to allocate *borrrowable* channels in such a way as to maximize the long term and/or short-term performance of the network. The performance metrics that can be used to evaluate the solutions proposed will be primarily the number of hosts blocked and the number of borrowings. A user is blocked when it enters a cell and cannot be allocated a channel. Obviously, the more hosts that are blocked, the worse will be the performance of the network. The other major metric is the number of channel-borrowings. This should be minimized because channel borrow requests generate network traffic. There are other metrics that can be used to evaluate the performance of the solution such as the number of "hot cells" that appear in a cellular environment.

There are a number of ways to deal with excess load in mobile networks in addition to channel borrowing, such as channel sharing and cell splitting. In particular cell splitting is commonly used in many real cellular networks. Cell splitting works by breaking down cells into smaller cells. This is accomplished by having several different levels of cell coverage. These different levels are often called macro-cells and micro-cells. A macro-cell is essentially an umbrella over a set of micro-cells. When traffic becomes too great for a cell to handle and there is a micro-cell structure in place, the cell can be switched out and the micro-cells switched in. This enables the original cell site to handle more load. There are obvious drawbacks to this scheme that prevent it being implemented throughout the network. The obvious problem is, of course, cost. A secondary concern is the extra network traffic introduced by the additional cells.

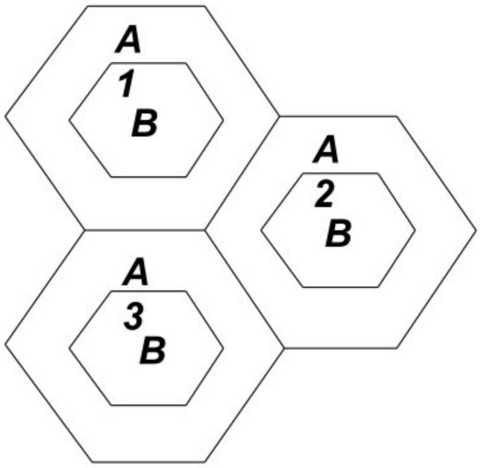

Figure 3: Illustrating a frequency reuse pattern

To provide greater frequency utilization, cells may be divided into concentric regions. In the region closest to the base station, channels can be used at low power without interfering with the same channels being used in the central regions of neighboring cells. For example, referring to Figure 3, each of the three cells has its own set of local frequencies legal to use in the cell at full power. In addition, a set B of frequencies (the same for all cells) can be used in each cell at a reduced power level to avoid interference.

Although these types of schemes increase the available bandwidth, they are complex to manage and introduce an imbalance between resources available for calls depending on the region in which they originate. There are numerous algorithms in the literature to solve the problem that fewer channels are available in the region furthest away from the base station, and to create a uniform CBP across an entire cell. Dividing a cell into regions also introduces the possibility of handoff being necessary when a mobile host moves from the inner to the outer region of a cell.

Handoff is a problem for QoS provisioning because the new region or cell that a mobile host is entering may not have the resources available to grant the same level of QoS that the hosts had originally negotiated or may not be able to continue the host's call at all. And as cells become smaller (as in micro-/pico- cellular networks), handoffs will occur much more frequently. Handoff detection is in itself a research issue. As a mobile host moves away from one base station and towards a neighboring base station, the signal from one will get progressively weaker and from the other progressively stronger, until in some overlap area, they become equal for a time. But other things, such as terrain, can also affect signal strength. In the literature there are numerous algorithms for accurate handoff detection. Similarly, there are different strategies for *handoff queuing* as a means to lower the CDP. If a user is in the area where it can hear the signals of two base stations and its destination cell cannot support it, it is placed into a queue, with the idea that maybe the resources for it will become available before the time when it is completely outside the range of its current base station.

Reducing the CDP, or the handoff failure rate, is more important than reducing the CBP, because we assume that it is more disturbing to users to have an ongoing call cut off, than to have a call attempt denied. Dynamic and flexible channel allocation schemes aid in lowering the CDP because channels can be allocated or borrowed when handoffs arrive and find no available bandwidth. A common technique for reducing dropped calls is to reserve some portion of the bandwidth in a cell for use only by handoffs. The simplest method of bandwidth or channel reservation is static, where a fixed set of channels, or fixed percentage of a cell's bandwidth, is set aside for handoffs. Selecting the amount of bandwidth to reserve is a trade-off between the CBP and CDP – the larger the reservation, the less bandwidth available for new calls. Dynamic or adaptive reservation uses information about the network or the mobile hosts to vary the amount of reserved bandwidth with the current conditions in order to reach the most optimal balance between CBP and CDP.

3. Satellite Networks

In response to the increasing demand for truly global coverage needed by Personal Communication Services (PCS), a new generation of mobile satellite networks intended to provide *anytime-anywhere* communication services was proposed in the literature (Jamalipour and Tung, 2001; Luglio, 1999) Low Earth Orbiting (LEO) mobile satellite networks, deployed at altitudes ranging from 500km to 2000km, are well suited to handle bursty Internet and multimedia traffic and to offer *anytime-anywhere* connectivity to mobile users. These satellite networks offer numerous advantages over terrestrial networks including global coverage and low cost-per-minute access to end-users equipped with hand-held devices. Since LEO satellite networks are expected to support real-time interactive multimedia traffic they must be able to provide their users with QoS guarantees.

3.1. Challenges

While providing significant advantages over their terrestrial counterparts, LEO satellite networks present protocol designers with an array of daunting challenges, including handoff, mobility and location management (Del Re et al, 2000; Nguyen et al., 2003; Nguyen et al., 2002; Olariu, 2005; Olariu et al., 2005a, 2005b; Olariu et al., 2003). Because LEO satellites are deployed at low-altitude, Kepler's third law implies that these satellites must traverse their orbits at a very high speed. We assume an orbital speed of about 26,000Km/h. Referring to Figure 4, the coverage area of a satellite – a circular area of the surface of the Earth - is referred to as its *footprint*. For spectral efficiency reasons, the satellite footprint is partitioned into slightly overlapping cells, called *spotbeams*. As their coverage area changes continuously, in order to maintain connectivity, users must switch from spotbeam to spotbeam and from satellite to satellite, resulting in frequent intra- and inter-satellite handoffs. In this work, we focus on intra-satellite handoffs, referred to, simply, as *handoffs*. A well-known strategy for reducing handoff failure is to reserve bandwidth for the exclusive use of handoff connections. In the *fixed reservation* approach, a fixed percentage of the available bandwidth in a cell is permanently reserved for handoff. In the *predictive reservation* strategy, bandwidth is reserved dynamically using a probabilistic approach.

Due to the large number of handoffs experienced by a typical connection during its lifetime, resource management and connection admission control are very important tasks if the system is to provide fair bandwidth sharing and QoS guarantees. In particular, a reliable handoff mechanism is needed to maintain connectivity and to minimize service interruption to on-going connections, as users roam about the system.

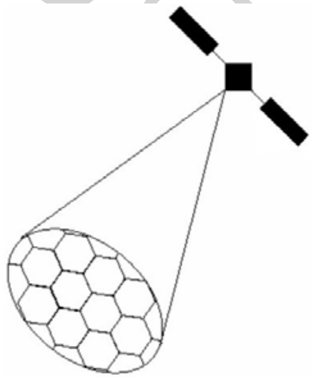

Figure 4: Illustrating a satellite footprint and spotbeams

3.2. Mobility Model and Traffic Parameters

Although several mobility models exist for LEO satellites (see, for example, Nguyen et al, 2003), it is customary to assume a one-dimensional mobility model where the users move in straight lines and at a constant speed, essentially the same as the orbital speed of the satellite. For simplicity, all the spotbeams (also referred to as *cells*) are identical in shape and size. Although each spotbeam is circular, we use squares to approximate spotbeams (we note that some authors use regular hexagons instead of squares).

The diameter of a cell is taken to be ; consequently, the time t_s it takes a user to cross a cell is, roughly, 65 seconds. Referring to Figure 5, the user remains in the cell where the connection was initiated for t_f time, where t_f is uniformly distributed between 0 and t_s. Thus, t_f is the time until the first handoff request, assuming that the call does not end in the original cell. After the first handoff, a constant time t_s is assumed between subsequent handoff requests until call termination.

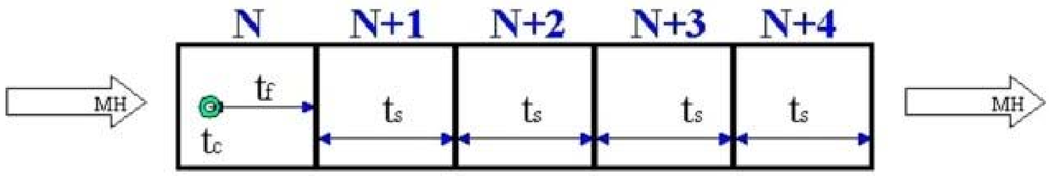

Figure 5: Illustrating some of the mobility and cell parameters

As illustrated in Figure 5, when a new connection is requested in cell N, it is associated with a *trajectory*, consisting of a list $N, N+1, N+2, \ldots, N+k$, of cells that the connection may visit during its lifetime. The holding times of the connections is assumed to be exponentially distributed with mean $1/\mu$..

Assume that connection C was accepted in cell N. After t_f time units, C is about to cross into cell $N+1$. Let p_f be the probability of this first handoff request. El-Kadi et al. (2001) have shown that

$$p_f = \frac{1-e^{-\mu t_s}}{\mu t_s}.$$

Moreover, (El-Kadi et al., 2001) have shown that the probability of the $(k+1)$-th handoff request is $e^{-\mu t_s}$ which, as expected, is independent of k. Consequently, we will let $p_s = e^{-\mu t_s}$ denote the probability of a *subsequent* handoff request. It is important to note that t_f, t_s, p_f and p_s are mobility parameters that can be easily evaluated by the LEO satellite using its on-board processing capabilities.

The traffic offered to the satellite system is assumed to belong to two classes:

- **Class I traffic** — real-time multimedia traffic, such as interactive voice and video applications, and
- **Class II traffic** — non real-time data traffic, such as email or ftp.

When a user requests a new connection C in a given cell, it provides the following parameters:

- the desired class of traffic for C (either I or II),
- M_C the desired amount of bandwidth for the connection.

If the request is for a Class I connection the following parameters are also specified:

- m_C the smallest amount of bandwidth that the source requires in order to maintain acceptable quality, e.g. the smallest encoding rate of its codec
- θ_C the largest acceptable CDP that the connection can tolerate
- $1/\mu_C$ the mean holding time of C.

-
-
-

Bibliography

Akyildiz, I.F., Su, W., Sankarasubramanian, Y., and Cayirci, E. (2002). Wireless sensor networks: A survey, *Computer Networks*, **38**(4), 393-422. [A fundamental reference to sensor networks and their applications]

Barnes, S. J. and Huff, S. L. (2003). Rising sun: iMode and the wireless Internet, *Communications of the ACM*, **46**(11), 79-84. [A good discussion of mobile commerce and its applications; a good discussion on the relevance of networking]

Chen, Y. and Liestman, A. (2003). A zonal algorithm for clustering ad hoc networks, *International Journal of Foundation of Computer Science*, **14**(2), 305-322. [An important paper that discusses clustering in ad hoc networks]

Del Re, E., Fantacci, R., and Giambene, G. (2000). Characterization of user mobility in Low Earth Orbiting mobile satellite systems, *Wireless Networks*, **6**, 165-179. [A good reference for mathematical derivations related to user mobility in LEO satellite networks]

El-Kadi, M., Olariu, S. and Todorova, P. (2001). Predictive resource allocation in multimedia satellite networks, *Proc IEEE, GLOBECOM* 2001, San Antonio, TX, November 25-29, 2001. [A paper dealing with resource allocation in LEO satellite networks]

Heinzelman, W., Chandrakasa, A., and Balakrishnan, H. (2000). Energy-efficient communication protocols for wireless microsensor networks, *Proc. Hawaiian International Conference on System Sciences*, (HICCS'33), Hawaii, January 2000. [One of the early papers on clustering and routing in sensor networks. A very good reference for later developments]

Jamalipour, A. and Tung, T. (2001). The role of satellites in global IT: trends and implications, *IEEE Personal Communications*, **8**(3), 5-11. [Contains an excellent survey of the role of satellites in the global IT]

K. H. Jones, K. N. Lodding, A. Wadaa, S. Olariu, L. Wilson, M. Eltoweissy (2005), Biomimetic models for sensor networks - towards a social sensor network, S. Olariu and A. Y. Zomaya Eds, *Handbook of Bio-Inspired Algorithmic Techniques*, CRC Press, Boca Raton, Florida 2005. [A good discussion on the bio-mimetic view of sensor networks]

Luglio, M. (1999). Mobile multimedia satellite communications, *IEEE Multimedia*, **6,** 10-14. [A very good survey of satellite communications]

Negpal, R. and Coore, D. (1997). An algorithm for group formation in an amorphous computer, AI Memo 1626, MIT. [A fundamental paper on distributed clustering]

Nguyen, H. N., Olariu, S., and Todorova, P. (2003). A novel mobility model and resource allocation strategy for multimedia LEO satellite networks, *Proc. IEEE WCNC*, Orlando, Florida, March 2003. [The paper contains a good discussion of mobility models in LEO satellite networks]

Nguyen, H. N., Schuringa, J., and van As,H. R. (2002). Handover schemes for QoS guarantees in LEO satellite networks, *Proc. ICON'2002*. [The paper contains a good discussion of resource management issues in LEO satellite networks]

Olariu, S. (2005). QoS provisioning Strategies in LEO Satellites, in M. Cheng, Y. Li, and D.-Z. Du (Eds.), *Combinatorial Optimization in Communication Networks*, Kluwer Academic Publishers, Dordrecht, The Netherlands. [A comprehensive survey of QoS provisioning in LEO satellite networks]

Olariu, S., Eltoweissy, M., Wadaa, A., Xu,Q. and Zomaya, A. Y. (2005a). Protecting the communication structure in sensor networks, *International Journal of Distributed Sensor Networks*, **1**, 187-204. [A paper that discusses the applications of a virtual infrastructure to securing wireless sensor networks]

Olariu, S., Rizvi, S. A., Shirhatti, R., and Todorova, P. (2003). Q-Win - A new admission and handoff management scheme for multimedia LEO satellite networks, *Telecommunication Systems*, **22**(1-4), 151-168. [The paper discusses Q-Win a simple and efficient resource management protocol for LEO satellite networks]

Olariu, S., Shirhatti, R. and Zomaya, A. (2005c). OSCAR - An opportunistic call admission protocol for LEO satellite networks, *Ad Hoc and Sensor Wireless Networks*, **1**, 255-275. [The paper discusses OSCAR a simple and efficient resource management protocol for LEO satellite networks]

Olariu, S., Wadaa, A., Wilson, L., and Eltoweissy, M. (2004). Wireless sensor networks: leveraging the virtual infrastructure, *IEEE Network*, **18**(4), 51-56. [A fundamental paper that addresses the problem of leveraging a general-purpose infrastructure to build efficient protocols for wireless sensor networks]

Olariu, S., Xu, Q., Wadaa, A. and Stojmonovic, I. (2005d). A Virtual Infrastructure for Wireless Sensor Networks, in I. Stojmenovic, Ed., *Handbook of Sensor Networks*, Wiley 2005, 107—140. [A fundamental paper that addresses the problem of leveraging a general-purpose infrastructure to build efficient protocols for wireless sensor networks]

Sohrabi, K., Gao, J., Ailawadhi, V., and Pottie, G. (2000). Protocols for self-organization of a wireless sensor network, *IEEE Personal Communications,* October 2000, 16-27. [An early paper on self-organizing wireless sensor networks]

Stojmenovic, I. (2005). *Handbook of Wireless Sensor Networks*, New York: Wiley. [A recent edited book on sensor networks]

Wadaa, A., Olariu, S., Wilson, L., Eltoweissy, M. and Jones, K. (2005). Training a wireless sensor network, *Journal of Mobile Networks and Applications*, (MONET), **10**, (2005), 151-167. [The basic paper that discusses building a virtual infrastructure in wireless sensor networks. Also the first paper to discuss the uneven energy depletion problem.

Wang, L. and Olariu, S. (2005). Cluster maintenance in mobile ad-hoc networks, *Cluster Computing*, **8**, 111118. [A very good discussion of clustering and cluster maintenance in ad hoc networks]

Wang, L. and Olariu, S. (2006). Towards a general-purpose virtual infrastructure for mobile ad-hoc networks, in Y. Xiao and Y. Pan (Eds.), *Ad Hoc and Sensor Networks*, Nova Science Publishers. [A very good discussion of clustering and cluster maintenance in ad hoc networks]

Xu, Q and Olariu, S. (2005). A simple and robust virtual infrastructure for massively deployed wireless sensor networks, *Computer Communications*, **28**, 15051516. [A recent paper dealing with clustering and communications in wireless sensor networks]

Ye, W., Heidemann, J. and Estrin, D. (2002). An energy-efficient MAC protocol for wireless sensor networks, *Proc. 21st International Annual Joint Conference of the IEEE Computer and Communications Society* (INFOCOM 2002), New York, June, 2002. [A good reference for MAC protocols in wireless

sensor networks]

Biographical Sketches

Chutima Boothum received her Ph.D. in Computer Science at Old Dominion University, 2006 and M.S. in Applied Computer Science at Illinois State University, 2000. She is currently an assistant professor at Hampton University. Her research interests are in areas of artificial intelligence, natural language processing, and computational linguistics. Professor Boonthum involves in developing a reliable communication (concerning both wired- and wireless network) between the delivery software and the central server for the online reading strategy trainer, called iSTART (Interactive Strategy Training for Active Reading and Thinking).

Stephan Olariu has held many different roles and responsibilities as a member of numerous organizations and teams. Much of his experience has been with the design and implementation of robust protocols for wireless networks and in particular sensor networks and their applications. Professor Olariu is applying mathematical modeling and analytical frameworks to the resolution of problems ranging from securing communications, to predicting the behavior of complex systems, to evaluating performance of wireless networks. His research interests are in the area of complex systems enabled by large-scale deployments of sensors and more specifically in securing systems of systems.

Ekaterina Shurkova is a Ph.D. in Computer Science at Old Dominion University. Her research interests are in the area of bio-mimetic aspects of wireless sensor networks.

Lan Wang received his Ph.D. in Computer Science at Old Dominion University, 2005 and both M.S. and B.S. in Computer Science at Harbin Engineering University, Harbin, China in 1995 and 1992, respectively. His dissertation was on "Mobile Ad Hoc Networks", under Professor Olariu's supervision. Dr. Wang's research interests are in the areas of ad hoc networks, sensor networks and QoS provisioning in wireless networks.

Qingwen Xu is a Ph.D. in Computer Science at Old Dominion University. His research interests are in the area of designing low-level protocols for wireless sensor networks.