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# Theatre in the Sky: A ubiquitous broadband multimedia-on-demand service over a novel constellation composed of quasi-geostationary satellites

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## SUMMARY

To meet an ever-growing demand for wideband multimedia services and electronic connectivity across the world, development of ubiquitous broadband multimedia systems is gaining a tremendous interest at both commercial and academic levels. Satellite networks will play an indispensable role in the deployment of such systems. A significant number of satellite communication constellations have been thus proposed using Geostationary (GEO), Medium Earth Orbit (MEO), or Low Earth Orbit (LEO) satellites. These constellations, however, either require a potential number of satellites or are unable to provide data transmission with high elevation angles.

This paper proposes a new satellite constellation composed of Quasi-GeoStationary Orbit (Quasi-GSO) satellites. The main advantage of the constellation is in its ability to provide global coverage with a significantly small number of satellites while, at the same time, maintaining high elevation angles. Based on a combination of this Quasi-GSO satellites constellation and terrestrial networks, the paper proposes also an architecture for building a global, large-scale, and efficient Video-on-Demand (VoD) system. The entire architecture is referred to as a 'Theatre in the Sky'. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: VoD; quasi-GSO satellites; GEO; LEO; MEO satellite systems

## 1. INTRODUCTION

The recent trend in telecommunications industry is toward ubiquitous information infrastructures [1]. Next-generation information systems should be able to offer a plethora of flexible multimedia services to a large population of users on demand, anywhere, anytime. Along with the rapid globalization of the telecommunications industry, the demand for these advanced multimedia services is growing in terms of both the number of users and the services to be supported. The new services gaining momentum include Video-on-Demand (VoD), broadcasting, telemedicine, and distance education.

Large-scale deployment of these bandwidth-intensive multimedia services places severe demands on terrestrial networks. Network technicians and telecommunications managers have envisaged optical-fibre networks and have considered temporary solutions such as

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Asynchronous Digital Subscriber Line (ADSL) and High-rate DSL (HDSL) technologies. However, due to the exponential growth of the Internet use and its worldwide acceptance, applying such solutions to bridge the last mile between local service providers and individual residences will require an immense investment in terms of time, infrastructure, and human resources. Building a cost-efficient global multimedia infrastructure is one of the major challenges before telecommunications industry in the 21st century. During this millennium, satellite communication systems will be an integral part of this infrastructure [2, 3]. They will open a promising and strong market for service providers and telecom operators [4, 5].

Satellite communication systems offer an array of advantages over traditional terrestrial networks. In addition to their inherent multicast capabilities and flexible deployment features, they are able to provide coverage to extensive geographic areas and interconnect among remote terrestrial networks (e.g. islands). They can be used also as an efficient alternative to damaged terrestrial networks to recover from natural disasters.

The key technologies required to support broadband multimedia communication over satellite systems have been already developed [6, 7]. Indeed, with the recent advancements in satellite return channels and on-board processing technologies, satellites are now able to provide full two-way services to and from earth terminals [8]. Additionally, several techniques for on-demand onboard switching have been proposed to make efficient use of satellites capacity [9]. Unlimited connectivity can be accordingly guaranteed. The advent of ka-band guarantees more availability of spectrum to support broadband multimedia communication [10]. This has spurred further on the expansion of multimedia satellite networks. To encourage the deployment of cost-effective terminals with small antennas (e.g. Very Small Aperture Terminals (VSATs) and Ultra Small Aperture Terminals (USATs)), satellite channels with higher frequencies, such as V-band (36–51.4 GHz) and millimeter wave (71–76 GHz), have also been developed. These high frequencies will enable greater mobility and ubiquitous connectivity across the world. Various mechanisms have also been proposed to cope with the well-known problems associated with rain and atmospheric attenuation at these frequencies. Given these advancements and on-going enhancements in satellite communications, it is now possible to design and implement communication satellite systems for multimedia applications.

In the recent literature, a number of Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary (GEO) satellite constellations have been proposed to provide broadband services. Table I lists some of these broadband satellite constellations. For more than two decades, GEO satellite systems have been used for providing commercial services. They have, however, failed in providing data transmission with high elevation angles over high latitude regions. In Tokyo, for example, the elevation does not exceed $48^{\circ}$. In GEO systems, terminals (mainly mobile nodes) experience frequent cut-offs of propagation signals by tall buildings, trees, or mountains due to possibly low elevation angles of the link above the horizon.

LEO and MEO satellite constellations rove the skies at zenith and consequently reduce the blockage events of the transmission links. Teledesic is a notable LEO example. Its original design consisted of 840 LEO satellites. It was, however, redesigned later and the number of required satellites was reduced to 288. All proposed LEO and MEO satellite constellations require a large number of satellites for global coverage. Use of a large number of satellites provides certainly more flexibility. It, however, leads to complex dynamic routing and mobility management issues caused by frequent handover occurrences [11, 12]. Furthermore, LEO or MEO satellites can be used for only a short life span.

 

Table I. Major GEO, MEO, and LEO satellite constellations.

| System | Organization | Constellation type | No. of satellites | Altitude (km) | Min. elevation angle (deg) | Coverage (%) | Inter-satellite links |
|---|---|---|---|---|---|---|---|
| NeLS | Japan NiCT | LEO | 120 | 1200 | 20 | 79 | Yes |
| Iridium | Motorola | LEO | 66 | 780 | 8.2 | 100 | Yes |
| Teledesic | Teledesic Co. | LEO | 288 | 1375 | 40 | 100 | Yes |
| Globalstar | Global Star Co. | LEO | 48 | 1406 | 10 | 83 | Yes |
| Skybridge | Alcatel | LEO | 80 | 1469 | 10 | 86 | No |
| Celestri | Motorola | LEO | 63 | 1400 | 16 | 73 | Yes |
| Spaceway | Hughes | GEO and MEO | 16 GEO | 35 786 | 20 | 86 | Yes |
| | | | 20 MEO | 10 352 | | | |
| Astrolink | Lockheed Martin Co. | GEO | 16 | 35 786 | 20 | 79 | Yes |

As a remedy to the above issues, this paper proposes a novel constellation composed of long life span Quasi-GeoStationary Orbit (Quasi-GSO) satellites. The strength of the constellation is its ability to provide global coverage with a significantly small number of satellites while, at the same time, maintaining high elevation angles. The architecture of the proposed constellation is dynamic in its nature, but exhibits significantly less mobility than LEO or MEO constellations.

The constellation constitutes an appealing alternative to GEO, LEO, MEO satellites. It constitutes also a desirable complement to earth-based networks; mainly when personal mobile or multimedia services are involved. In this regard, the paper proposes also an architecture based on a combination of the Quasi-GSO satellite constellation and terrestrial networks for building a significantly large-scale and efficient VoD system.

The remainder of this paper is structured as follows. Section 2 gives a brief description of the Quasi-GSO satellite systems and their main merits. The key design philosophy and distinct features that were incorporated in the proposed constellation are presented in Section 3. Section 4 portrays the proposed VoD architecture, 'Theatre in the Sky'. Operational details as well as various underlying network assumptions are also discussed in this section. The paper concludes in Section 5 with a summary recapping the main advantages and achievements of the proposed constellation.

## 2. QUASI-GSO SATELLITE SYSTEM

Without loss of generality, current broadband satellite systems can be classified into two types: low-altitude earth orbit or geostationary satellite systems. The former requires a huge infrastructure investment and has created some doubts on its economical practicality mainly after the recent financial failure of the Iridium system. The latter, on the other hand, fails to provide a consistently high-elevation angle and consequently experiences very often incidences of signal propagation cut-off due to tall buildings or mountains.[‡] Needs for a system where satellites have

[‡] Mainly when mobile terminals are involved.

 

a clear 'line of sight' to the ground, in conjunction with coverage of high-latitude regions, have sparked the development of new cost-effective satellite communication systems called Quasi-GSO satellite systems [13].

Quasi-GSO satellite systems provide constant coverage over a particular area of the Earth through employment of a series of satellites. The Quasi-GSO satellites complete one full orbit per day in synchronization with the Earth's rotation, describing a north–south figure of eight locus centred around a point on the equator (Figure 1). The Quasi-GSO satellite system consists of at least three satellites placed in circular orbits at an inclination angle of approximately 45° relative to the Equator (Figure 2). The satellites are placed in orbit such that one would be positioned almost directly above the target area at any given point in time. The Quasi-GSO satellites guarantee a minimum angle of elevation of at least 60° and higher values of elevation angle can be achieved by using more than three satellites. Figure 3(a) and (b) show the variation of the elevation angles of a Quasi-GSO system made of three satellites at two points on Earth, namely Tokyo and Sydney, respectively.

Quasi-GSO satellite systems are a promising alternative to conventional satellites in geostationary or low-altitude orbits. They can deliver huge amounts of broadcasts at high speed with

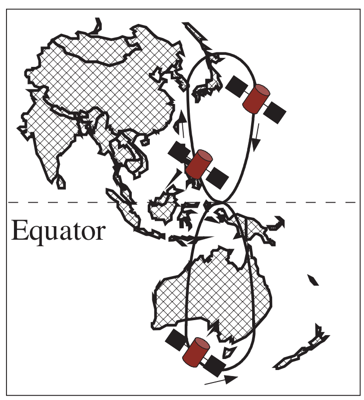


Figure 1. An example of a Quasi-GSO satellite system made of three satellites.

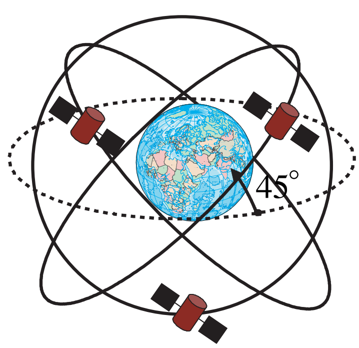


Figure 2. Circular orbits of Quasi-Geostationary satellites.

 

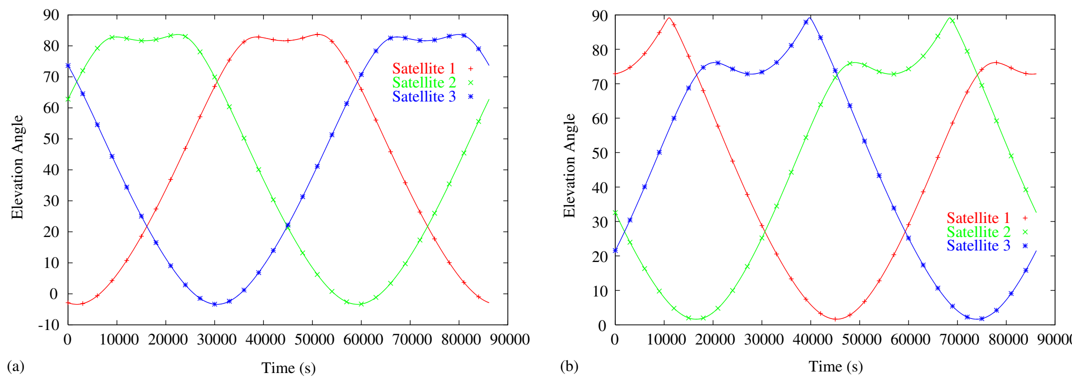


Figure 3. Elevation angle variation of the three satellites: (a) Tokyo; (b) Sydney.

high quality, and without being obstructed by tall buildings. They have been considered efficient for vehicular satellite communications, frequency sharing in fixed satellite communications, positioning systems, and north and south polar regions observation. In addition, they are particularly well suited to the provision of VoD, a service where signal propagation blockings are not tolerated. It should be stressed that the inherent issues with latency of Quasi-GSO satellites should not pose challenges for the delivery of high-quality multimedia. This paper aims to study how a constellation of these satellites could be used to provide global broadband multimedia-on-demand services.

## 3. OVERVIEW OF THE QUASI-GSO SATELLITE CONSTELLATION

The abstract configuration of the constellation is conceptually depicted in Figure 4. The figure portrays the orbits of six Quasi-GSO systems. Each system consists of three satellites, giving rise to only 18 satellites in the whole constellation. Setting the minimum value of the elevation angle to $40^\circ$, the constellation can provide coverage to the whole globe. It should be emphasized that the constellation can provide elevation angles largely higher than $40^\circ$ over middle-latitude regions. Table II summarizes the parameters of the constellation.

The longer life span of satellites in geosynchronous orbits, in conjunction with the small number of required satellites, makes the cost of the whole constellation more reasonable than most proposed LEO or MEO systems. Moreover, due to the insignificant mobility characteristic of the constellation, the mobility management-related cost of the system becomes cheaper.

Concerning inter-satellite links, two types are considered: Intra-System and Inter-System links. Intra-System links refer to the three links that connect the three satellites of a given system, and are dubbed *Intra-System Inter-Satellite Links* (Intra-SISLs) throughout this paper. Conversely, Inter-System links represent the three links that join between a satellite of a given system and its correspondent in the neighbouring system. Inter-System links are referred to as *Inter-System Inter-Satellite Links* (Inter-SISLs) throughout this paper. It should be noted that Inter-SISLs are of fixed length, whereas Intra-SISLs vary in length. For ease of illustration of Figure 4, both Inter-System and Intra-System links are not plotted.

 

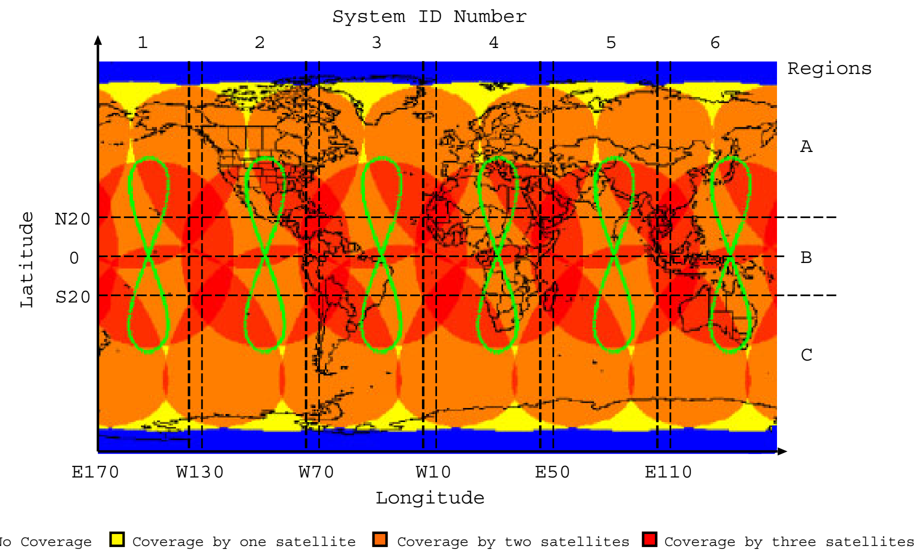


Figure 4. Illustration of the proposed Quasi-GSO constellation. (This is an edited image, generated by satellite constellation visualizer (SaVi), at http://sourceforge.net/projects/savi/).

Table II. Orbit parameters of the proposed constellation.

| Orbit parameter | Value |
|---|---|
| Orbital altitude | 35 780 km |
| Orbit inclination | 45° |
| Number of satellites | 18 |
| No. of orbits | 6 |
| No satellites per orbit | 3 |
| Eccentricity | 0 (circular orbit) |
| Difference angle of ascending node between adjacent orbit planes | 120° |
| Minimum elevation angle from user | 40° |

Referring to Tables I and III, a comparison of the proposed constellation to other satellite constellations can be made. The Quasi-GSO constellation is capable of providing almost global coverage with less number of satellites and high elevation angle. The frequency of handover occurrences in the constellation is significantly lower compared to that of LEO or MEO constellations (3–6 handovers per day). The network topology is hence simple and easy to manage. On the other hand, the round trip propagation delay is around 250 ms. The constellation is thus not suitable for delay-sensitive applications. It can be, however, a good candidate for the provision of applications that are not affected by long latency. Notable examples are VoD, live broadcasting, distance learning, online radio, messaging, and Global Positioning System services (GPS).

Although the mobility of the proposed Quasi-GSO satellite constellation is insignificant in comparison with LEO or MEO constellations, end-terminals are not always continuously

 

Table III. Important features of the proposed constellation.

| System | Organization | Constellation type | No. of satellites | Altitude (km) | Min. elevation angle (deg) | Coverage (%) | Inter-satellite links |
|---|---|---|---|---|---|---|---|
| Quasi-GSO | — | GEO | 18 | 35 786 | 40 | 96 | Yes |

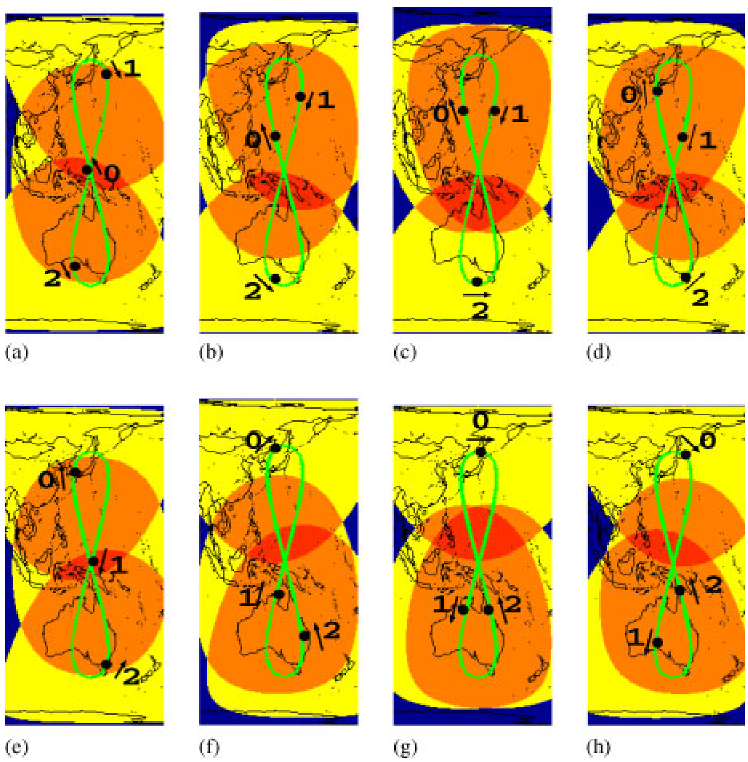

Figure 5. Coverage variation of a Quasi-GSO system. $T$ time the constellation is in initial position; $t$ time elapsed in hours. (These are edited images, generated by satellite constellation visualizer (SaVi), at http://sourceforge.net/projects/savi/): (a) $t = T$; (b) $t = T + 1$ h; (c) $t = T + 2$ h; (d) $t = T + 3$ h; (e) $t = T + 4$ h; (f) $t = T + 5$ h; (g) $t = T + 6$ h; and (h) $t = T + 7$ h.

connected to the same satellite in the constellation during the entire communication time. Handover of *Ground to Satellite Link* (*GSL*) to a new satellite may be thus required during the connection time. Having the minimum elevation angle set to 40°, diversity coverage becomes rife in this type of constellation. Figure 5 shows the variation of the diversity coverage of one Quasi-GSO satellite system over a time interval of 8 h.[§]

[§]The constellation returns back to its initial position every 8 h.

 

To cope with issues related to the initial set-up of connections or handover phenomenon, end-terminals are acquired with the ability of selecting the most appropriate satellite. The satellite selection scheme is developed based on dividing the coverage area of the constellation into a number of well-defined regions. Similarly in the spirit of Reference [14], selection of the most appropriate satellite depends on the geographical location of terminals and the handover occurrence time. In Reference [15], the performance of this geographical location-based satellite selection scheme was evaluated and compared to that of the widely used baseline satellite selection scheme. The latter simply selects the satellite with the highest elevation angle during the initial set-up of connections or upon a handover occurrence [16]. Extensive simulation results elucidated the better performance of the geographical location-based satellite selection scheme in reducing both the overall delay and delay variation. Another credit of the geographical location-based scheme consists in eliminating the last hop ambiguity that exists in LEO and MEO constellations. Indeed, since terminals in a geographical location should be necessarily connected to a known satellite, packet forwarding among satellites can be performed according to a geographical location-based routing protocol as proposed in Reference [17]. This reduces significantly the additional overhead that may be due to routing procedures.

## 4. THEATRE IN THE SKY: KEY COMPONENTS OF THE VOD ARCHITECTURE

This section describes how an integration of the above-mentioned Quasi-GSO satellite constellation with terrestrial networks can turn into an efficient architecture for the provision of global broadband multimedia services, beyond time and space limitations. The entire architecture and its components are conceptually depicted in Figure 6. The figure portrays the coverage areas of

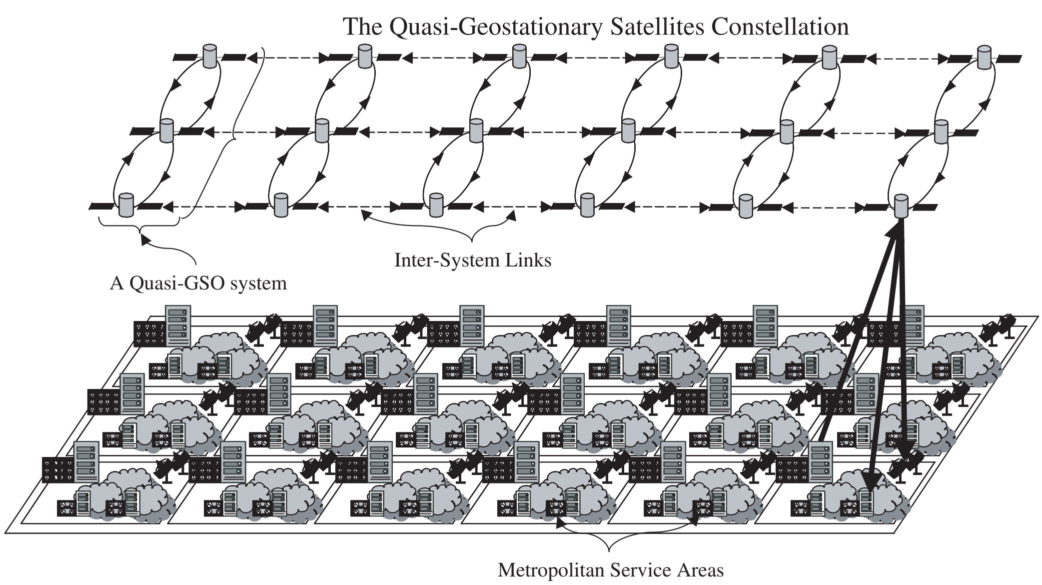


Figure 6. Theatre in the Sky: use of the Quasi-GSO satellites constellation to provide global broadband multimedia-on-demand services.

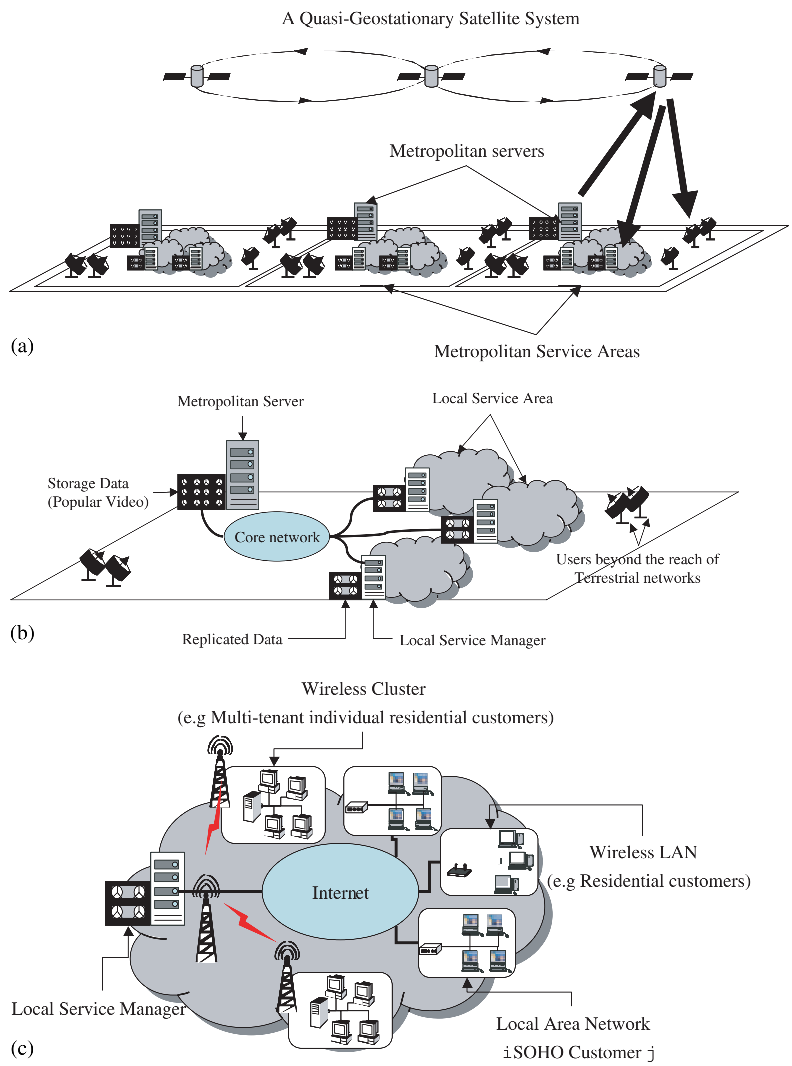


Figure 7. Hybrid network architecture: (a) the coverage area of a Quasi-GSO satellite system divided into a number of MSAs; (b) a metropolitan service area comprising a number of LSAs; and (c) an example of a LSA.

six Quasi-GSO systems. Each system consists of three satellites. The coverage area of each system is divided into a number of wide service areas as shown in Figure 7(a). These wide service areas are referred to as Metropolitan Service Area (MSA) throughout this paper. Each MSA comprises a single metropolitan VoD server and is determined in a way that the metropolitan server would always maintain multicast transmissions to end-users via only one satellite. This would help to avoid the often unpredictable delay variations and jitter that may be due to handover phenomenon. Obviously, the number of MSAs should be larger or equal to the number of satellites in the considered Quasi-GSO system. Terrestrial receivers, within a given MSA, are connected to the correspondent metropolitan server via the Quasi-GSO system. Uplinks refer to transmission from metropolitan video servers to the satellites. Conversely, downlinks refer to multicast transmissions from the satellites to end-users.

Figure 7(b) shows an example of an MSA. The illustrated MSA architecture consists of a number of clusters of clients inter-connected via the MSA network backbone. These clusters are referred to as Local Service Areas (LSAs) throughout this paper. The MSA area may include also some individual users in remote areas outside the reach of terrestrial infrastructure.

Figure 7(c) depicts a typical example of an LSA. An LSA cluster contains a local VoD service manager and a mini video server. The service manager operates authentication and schedules requests for forwarding to the mini video server. The service manager uses information about outstanding requests and the availability of resources to accept or reject requests. Practically, when a request for service arrives, the manager decides whether to deny or to accept this request. If the video server cannot take additional requests without degrading the quality of service of existing users or causing network congestion, the manager may block the request and send an immediate message to inform the customer that the request has been blocked and that there is a need to leave the session. Otherwise, the request will be admitted and the video server will be then requested to allocate a set of available resources to handle the request. The manager should be able to guarantee a continuous and high throughput, above all, while meeting real-time features. The mini video server is responsible for processing manager signallings and retrieving adequate data from its storage media. The LSA clusters are formed according to the geographical proximity and the density of end-users. Their determination should be also performed in a way that the mechanisms for accessing and delivering video data are sufficiently fast, reliable and easy to adapt to users' needs. The LSA network may be made of a hybrid network containing wireless LANs and some LANs inter-connected through the LSA Internet. These wireless LANs or terrestrial LANs can be multi-users platforms, such as corporations/enterprises, schools/universities, small office/home office (SOHO), or residential buildings, where many users are located in the same region and may desire to retrieve the same content over the LSA Internet.

Popular video titles are stored at metropolitan servers and repeatedly transmitted on staggered multicast channels. For each metropolitan server, the choice of these video titles is made while taking into account the cultural background, ethnicity, and spoken language of users within the given MSA. Over each MSA, individual users in remote areas outside the reach of terrestrial networks are simply serviced via the staggered multicast channels. As for fixed nodes within the reach of terrestrial networks, they are serviced according to the neighbours-buffering policy, a recently proposed scheme for VoD delivery [18]. Indeed, if a user request comes in between staggered start times of two adjacent multicast channels, the user joins to the most recently started multicast session and then requests the missing part from a nearby neighbour instead of receiving it from a patching unicast channel at a local server. Savings in these unicast channels will be exploited to satisfy requests coming from mobile nodes roaming within the coverage area of the satellite system [19]. To allow users to receive their VoD applications with higher degree of mobility and to guarantee a smooth streaming of video data, handoff-related schemes, such as that proposed in Reference [20], can be considered as well in the implementation of the architecture.

 

## 5. CONCLUDING REMARKS

In this paper, a novel satellite constellation was proposed. The constellation comprises six Quasi-GSO satellite systems. Each Quasi-GSO system consists of three satellites. The positions of the systems are decided in a manner that most dense cities with tall buildings (e.g. New York City) or mountainous regions are entirely covered by the systems. The constellation would be able then to cover most populated regions of Earth with only 18 satellites. Observing that the first and third systems (Figure 4) cover the Pacific and Atlantic oceans, respectively, and since signal blockings are not an issue in such areas, the number of satellites in the constellation can be further reduced to 12 by removing the two systems from the constellation. The constellation maintains transmission with a minimum elevation angle of $40^\circ$. High-latitude regions that have been deprived from transmission with high-elevation angles, should no more experience signal blockings. Furthermore, the constellation is fairly easy to manage because of its small number of satellites and less mobility characteristic.

The constellation is a good infrastructure for providing delay-insensitive multimedia applications, such as VoD and distance learning. We thus proposed an architecture based on a combination of this Quasi-GSO satellite constellation and existing terrestrial networks for building a large-scale and efficient VoD system. The proposed architecture is dubbed 'Theatre in the Sky'. It is hierarchically distributed. The coverage area of each Quasi-GSO satellite system is divided into a number of Metropolitan Service Areas, each comprising a single metropolitan VoD server. Popular video titles are stored at the MSA server and repeatedly transmitted on staggered multicast channels. In turn, each MSA is subdivided into a number of Local Service Areas according to geographical proximity and users density. Each LSA contains a service manager and a mini server.

Finally, it is our hope that the findings in this paper may contribute in the construction of a new constellation and help to a better understanding of Quasi-GSO systems while stimulating further work in the area.

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