A global Video-on-Demand Architecture Based on a Novel Constellation Composed of Quasi-Geostationary Satellites

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Abstract

Satellite networks are going to play an indispensable role in the deployment of ubiquitous broadband multimedia systems. In this context, this paper considers a recently-proposed satellite constellation composed of Quasi GeoStationary Orbit (Quasi-GSO) satellites to provide a global and cost-effective Video-on-Demand (VoD) service. The main advantages of the constellation consist in its ability to provide global coverage with a significantly small number of satellites while, at the same time, maintaining high elevation angles. Making use of these advantages and based on a combination of this Quasi-GSO satellites constellation and terrestrial networks, this paper proposes an architecture for building a global, large -scale, and cost-efficient Video-on-Demand (VoD) system. The entire architecture is referred to as *"Theatre in the Sky"*.

Keywords

Satellite broadcasting, Quasi-Geostationary satellites, Video-on-Demand, satellite constellations

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***Abstract*— Satellite networks are going to play an indispensable role in the deployment of ubiquitous broadband multimedia systems. In this context, this paper considers a recently-proposed satellite constellation composed of Quasi GeoStationary Orbit (Quasi-GSO) satellites to provide a global and cost-effective Video-on-Demand (VoD) service. The main advantages of the constellation consist in its ability to provide global coverage with a significantly small number of satellites while, at the same time, maintaining high elevation angles. Making use of these advantages and based on a combination of this Quasi-GSO satellites constellation and terrestrial networks, this paper proposes an architecture for building a global, large-scale, and cost-efficient Video-on-Demand (VoD) system. The entire architecture is referred to as *"Theatre in the Sky"*.**

***Keywords*– VoD, Quasi-GSO satellites, GEO, LEO, and MEO satellite systems.**

I. Introduction

The demand for 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, tele-medicine, and distance education. Large-scale deployment of these bandwidth-intensive multimedia services places severe demands on terrestrial networks as it requires an immense investment in terms of time, infrastructure, and human resources. Building a cost-effective global multimedia infrastructure is one of the major challenges before telecommunications industry in the 21^{st} century. During this millennium, satellite communication systems will be an integral part of this infrastructure [1] [2].

Given the advances and on-going enhancements in satellite communications, it is now possible to design and implement communication satellite systems for multimedia applications [3]. 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 [4]. Additionally, several techniques for on-demand onboard switching have been proposed to make efficient use of satellites capacity [5]. Unlimited connectivity can be accordingly guaranteed. The advent of Ka-band channels guarantees more availability of spectrum to support broadband multimedia communication [6]. 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 been also developed. These high frequencies will enable greater mobility and ubiquitous connectivity across the world.

In this context, this paper considers a recently-proposed satellite constellation for the provision of VoD services. The constellation is composed of long-life span Quasi-GeoStationary Orbit (Quasi-GSO) satellites. It constitutes a promising alternative to Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary (GEO) satellite constellations, mainly when personal mobile or multimedia services are involved. Based on a combination of this Quasi-GSO constellation and terrestrial networks, the paper proposes an architecture for building a significantly large-scale and cost-efficient VoD system. The proposed architecture is dubbed *"Theatre in the Sky"*.

The remainder of this paper is structured as follows. Section II gives a brief description of the Quasi-GSO satellite constellation and its main merits. Section III portrays the key components of the proposed VoD architecture, *"Theatre in the Sky"*. Section IV analytically develops the proposed architecture and discusses the analytical results. The paper concludes in Section V.

II. Overview of the Quasi-GSO Satellite Constellation

In the recent literature, a number of LEO, MEO, and GEO satellite constellations have been proposed to provide broadband services. Despite the wide usage of GEO satellite systems during the last two decades, they do not provide data transmission with high elevation angles over high latitude regions. This fact makes terminals (mainly mobile nodes) experience frequent cut-offs of propagation signals due to high buildings, trees, or mountains. On the other hand, whilst LEO and MEO satellite constellations rove the skies at zenith and consequently reduce the blockage events of the transmission links, they 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 [7] [8].

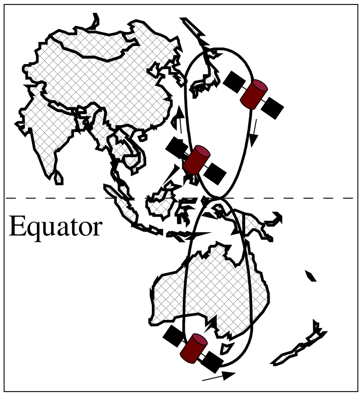


Fig. 1. An example of a Quasi-GSO satellite system made of three satellites

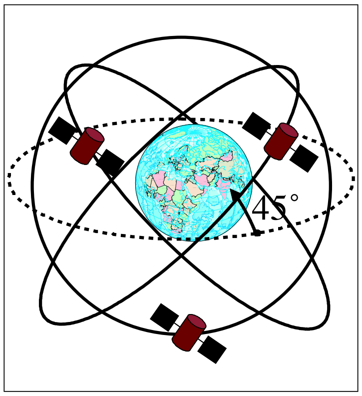


Fig. 2. Circular orbits of Quasi-Geostationary satellites

The development of new satellite communication systems called Quasi-Geostationary Orbit satellite systems [9] has come to satisfy needs for a cost-effective system where satellites can cover high latitude regions while maintaining a clear "line of sight" to the ground. 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 centered around a point on the equator (Fig. 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 geostationary orbit (Fig. 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.

In [10], the authors proposed a novel constellation composed of the above-mentioned Quasi-GSO satellite systems. The abstract configuration of the constellation is conceptually depicted in Fig. 3. The figure portrays the orbits of six Quasi-GSO systems. Each system consists of three satellites. The positions of the systems can be decided in a manner that most dense cities with high 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. The number

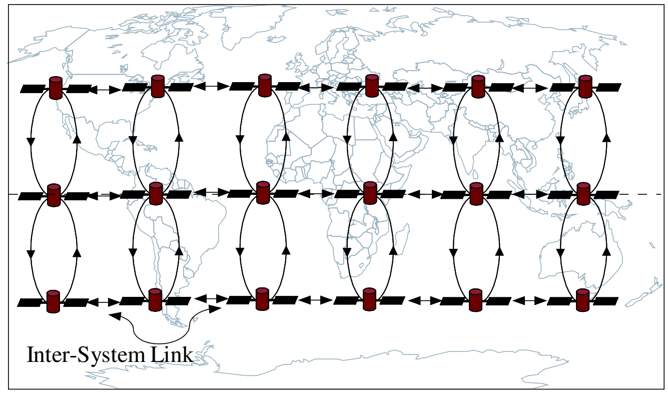


Fig. 3. Illustration of the Quasi-GSO satellites constellation

of satellites in the constellation can be further reduced to 12 by removing the two systems that cover the Pacific and the Atlantic oceans as signal blockings are not an issue in such areas. 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. Conversely, Inter-System links represent the three links that joint between a satellite of a given system and its correspondent in the neighboring system. Setting the minimum value of the elevation angle to 40°, the constellation can provide coverage to the whole globe. It should be emphasized that the constellation can provide elevation angles largely higher than 40° over middle-latitude regions. Table I summarizes the parameters of the constellation.

TABLE I

ORBIT PARAMETERS OF THE QUASI-GSO CONSTELLATION

Orbit Parameter	Value
Orbital altitude	35780km
Orbit inclination	45°
Number of satellites	18
No. of orbits	6
No of satellites per orbit	3
Eccentricity	0 (circular orbit)
Difference angle of ascending node between adjacent orbit planes	120°
Minimum elevation angle from user	40°

Compared to conventional GEO or LEO constellations, the Quasi-GSO constellation is capable of providing almost global coverage with significantly less number of satellites and high elevation angle. 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 constellation becomes cheaper also. The constellation can be a good candidate for the provision of a diverse set of services where signal propagation blockings are not tolerated. Notable examples are VoD, live broadcasting, distance learning, online radio, messaging, and Global Positioning System services (GPS). The remainder of this paper describes how an integration of this Quasi-GSO satellite constellation with terrestrial networks can turn into a cost-efficient architecture for the provision of global broadband multimedia-on-demand services.

III. Theatre in the Sky: Key Components of the VoD Architecture

As shown in Fig. 3, the abstract configuration of the constellation consists of the coverage areas of six Quasi-GSO systems. Each system is composed of three satellites. In the proposed VoD architecture, the coverage area of each system is divided into a number of wide service areas, referred to as Metropolitan Service Areas (MSAs). Fig. 4 shows an example of an MSA area. The illustrated MSA architecture consists in turn of a number of clusters of clients inter-connected via the MSA Internet. These clusters are referred to as Local Service Areas (LSAs). They are formed according to the geographical proximity and the density of end-users. The LSA network is made of a hybrid network containing 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. The MSA area may include also some individual users in remote areas outside the reach of terrestrial infrastructure.

Each MSA area comprises a single metropolitan VoD server with a total of N_m multicast channels and N_u unicast channels[1]. Popular titles are stored at metropolitan servers and repeatedly transmitted on the multicast channels of the server. It should be noted that each MSA server stores different video items and the choice of these video titles is made while taking into account the cultural background, ethnicity, and spoken language of users within the MSA region in question. Videos are assumed to follow a popularity distribution specified by $\{P_k|k = 1, 2, ...N_v\}$ where P_k is the probability of the k^{th} video title to be selected. To assign the multicast channels according to the viewing probability of video titles, the number of multicast channels allocated to the k^{th} video, n_k, is:

$$n_k = \frac{\sqrt{P_k} \cdot N_m}{\sum_{j=1}^{N_v} \sqrt{P_j}} \quad (1)$$

Using a simple staggered multicast schedule, adjacent multicast channels streaming the same video item are offset by a fixed time slot, ranging from a few minutes to tens of minutes. Assuming the number of multicast channels allocated for the k^{th} video, n_k, to be divisible by the length of the video, L, the time slot W_k, in seconds, is simply:

$$W_k = \frac{L}{n_k} \quad (2)$$

For each multicast channel, the assigned video is repeatedly multicast over the service time regardless of the number of active users or the load of the server, and data transmission from multicast channels is possible at only the beginning of slots.

A LSA cluster contains a local VoD service manager and a mini video server with a limited number of patching unicast channels. At the mini video server, the initial portions of video titles, contained in the metropolitan server's video library, are replicated. The service manager uses information about outstanding requests and the availability of resources at the mini-server to accept or reject requests.

Terrestrial receivers, within a given MSA area, are connected to the correspondent metropolitan server via the Quasi-GSO system. Over the same MSA area, individual users in remote areas outside the reach of terrestrial networks are simply served via the staggered multicast channels. As for fixed nodes within the reach of terrestrial networks, they are serviced according to the Neighbors-Based Buffering (NBB) policy, a recently-proposed scheme for VoD delivery [11]. 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 neighbor 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. 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 [12], can be considered as well in the implementation of the architecture. Over the entire constellation, if a user A in a MSA A generates a request at time t_r for a particular video item available only at the metropolitan server of a different MSA; MSA B, the metropolitan manager of MSA B first checks the start time of the nearest upcoming multicast channel C_n transmitting the requested movie. Let t_n be this start time. If the waiting time, $(t_n - t_r)$, is smaller than a predetermined admission threshold [2] δ as follows:

$$t_n - t_r \leq \delta$$

The request of user A will be immediately scheduled for the upcoming channel. If the waiting time is bigger than the admission threshold δ, the user A will then receive the already transmitted (from the nearest previous multicast channel C_{n-1}) portion of the video item from a unicast stream of the metropolitan server and start playing the movie as soon as data become available. Simultaneously, user A will receive the remaining portion of the movie from the nearest previous multicast channel C_{n-1} and store it in his/her local storage for later playback.

IV. Performance Evaluation

In this section, we attempt to analytically evaluate the performance of the proposed architecture. Without loss of generality, all the MSA servers are assumed to be similar. They are assumed to serve N_v popular titles of average length L seconds. In the numerical analysis, the number of video items, N_v, the average length of videos, L, and the admission threshold, δ, are set to 10, $90min$, and $90s$, respectively. It is assumed that all multicast and unicast streams are statistically

[1] A channel is defined as the unit for resource allocation and includes network bandwidth as well as server bandwidth.

[2] The parameter δ depends on how long the system is willing to let customers wait, and should not be more than few seconds to guarantee short latency service.

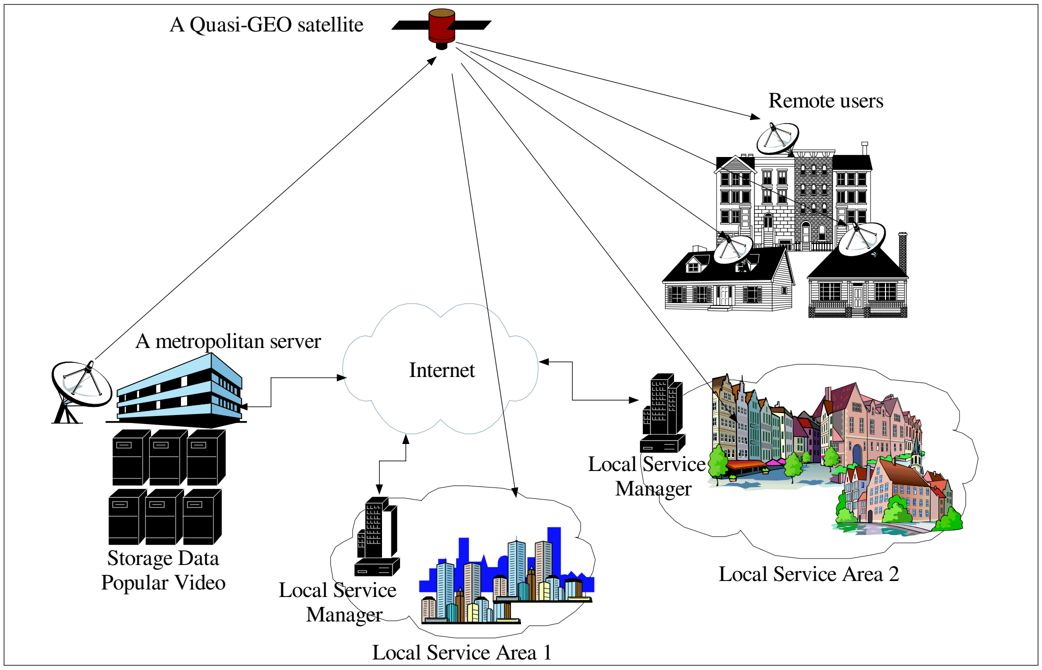


Fig. 4. A Metropolitan Service Area comprising a number of Local Service Areas. MSAs are determined in a way that metropolitan servers would always maintain multicast transmissions to end-users via only one Quasi-GSO satellite.

identical with a transmission capacity C. The request arrival process is assumed to be Poisson with arrival rate λ.

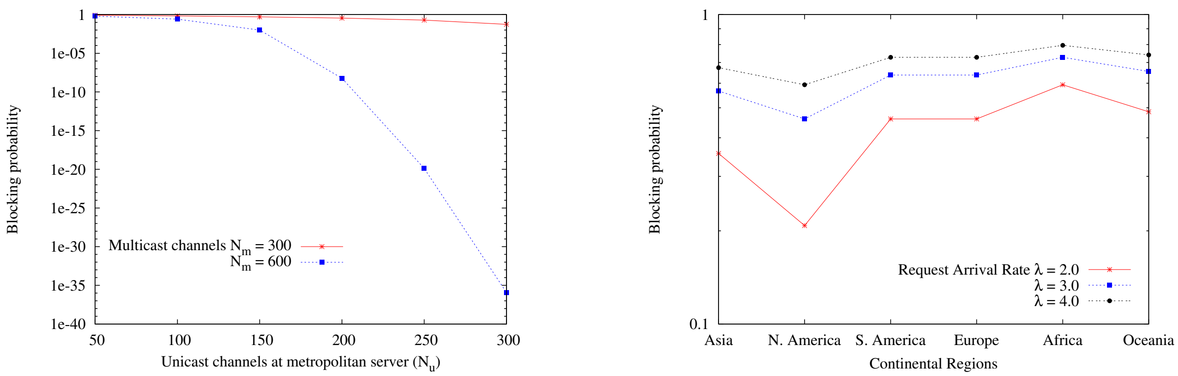
In the proposed architecture, each continent comprises a certain number of metropolitan servers depending on different factors such as the technical advances of the continent and the size of its population. For ease of analysis, we assume that each continent contains only one "virtual" metropolitan server with a number of unicast and multicast channels equal to the total unicast and multicast channels of all the metropolitan servers in that continent. Users from the six continental regions issue requests following a distribution as shown in Table II. This distribution is similar in spirit to the traffic distribution used in [13].

As has been explained earlier, the service times of requests arriving at the metropolitan server depend on their arrival time t_r and the start time t_{n-1} of the most recently started multicast channel C_{n-1}. Since $0 \leq t_r - t_{n-1} \leq W_k - \delta$, the service times for requests entering the unicast channel queue of the metropolitan server can be assumed to be uniformly distributed over the time interval $[0 : W_k - \delta]$. The N_u unicast channels can be thus modeled as an M/M/N/N+n queue, where N is the queue capacity ($N = N_u$). No queuing is assumed in the analysis ($n = 0$), for the simple reason that queuing may cause longer service response delay in case of high arrival rates, which may ultimately effect the short-latency nature of VoD service. We compute numerical results from the M/M/n/n+N queuing model to evaluate the capacity of the metropolitan servers in the proposed architecture in terms of blocking probability.

To better evaluate the system's performance, we first consider the case of only one metropolitan server (e.g. Asia). The arrival request rate is set to 4 ($\lambda = 4.0$) and two scenarios are considered by setting the number of multicast channels N_m to 300 and 600, respectively. We investigate the capacity of the system for different number of unicast channels N_u. Fig. 5(a) illustrates the numerical results. The figure indicates that the blocking probability decreases as more unicast channels are available. Note that a decrease in the blocking probability can be translated into higher capacity of the server. While this result is obvious, the figure shows that higher numbers of multicast channels significantly increase the capacity of the system. This result is attributed to the fact that by increasing the number of multicast channels, the slot time W_k of each video item decreases, and the service time $(W_k - \delta)$ of the unicast channel queue decreases accordingly. This reduces the number of requests that should be satisfied during the service time, and thus increases the capacity of the system. To evaluate the "global" performance of the architecture, we plot the blocking probability of the metropolitan servers in the six continental regions of the world for different loads in Fig. 5(b). The number of unicast and multicast channels of each server are set to 100 and 300, respectively. The figure shows that the highest blocking probability is experienced by the metropolitan server in "Africa" as most of the user requests come from outside the continent. On the other hand, Asia and North America experience the lowest blocking probability and that is due to the fact that most of the user requests originate from within the two regions. Finally, it should be admitted that the numerical results depend largely on the considered distribution of the user requests. In addition, it should be emphasized that whilst the assumption of having similar metropolitan servers at the six continents regardless of each continent's economic power, population size, and technical advances may be unsound, the obtained numerical results give good insight into the performance of the proposed architecture.

TABLE II
PERCENTAGE OF TOTAL USER REQUESTS AMONG THE SIX CONTINENTAL REGIONS

	Destination					
Source	N. America	S. America	Europe	Africa	Asia	Oceania
N. America (%)	60	10	15	2	10	3
S. America (%)	35	40	12	2	8	3
Europe (%)	40	5	40	2	10	3
Africa (%)	40	2	30	20	5	3
Asia (%)	30	2	10	2	50	6
Oceania (%)	40	2	10	2	12	34



(a) Performance of the metropolitan server in Asia for different numbers of multicast and unicast channels ($\lambda = 4.0$)

(b) Performance of the metropolitan servers in the six continental regions of the world ($N_m = 300, N_u = 100$)

Fig. 5. Numerical results in terms of the blocking probability

V. CONCLUSION

In this paper, we proposed an architecture based on a combination of the recently-proposed Quasi-GSO satellite constellation and existing terrestrial networks for building a large-scale and cost-effective 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. A different set of mechanisms is considered for satisfying user requests from within and outside MSA regions. A simple analysis is developed to evaluate the capacity of the architecture for different numbers of unicast and multicast channels. Finally, it is our hope that the findings in this paper may contribute in the construction of a global and cost-effective satellite-based multimedia-on-demand infrastructure while stimulating further work in the area.

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