Satellite Communications, and Mathematical Modeling for Satellite Orbits and Signal Propagation - a Tutorial and short Review

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Abstract

The designing and development of the systems, for the fascinating field of the satellite communications has drawn the attention of various researchers. The concepts, types, and applications of the satellite communications have been presented in a tutorial form. The terms - Satellite Orbits, Frequency Bands, Capacity Allocation, Radio Signal Propagation, and Laser Communications have been briefly described. The mathematical equations for evaluating the effect of height of the orbit on the time period, and the ratio of the power available at the input of the receiving antenna, to the output power at the transmitting antenna have been presented. A short review of the recent research activities in the satellite communications has been presented. The paper is expected to be useful for the new entrants to the field, and also those engaged in the design and development of the new systems.

Keywords: Satellite Communications, Frequency Bands, and Laser Communications.

Resumen

El diseño y desarrollo de los sistemas, para el fascinante campo de las comunicaciones por satélite, ha llamado la atención de varios investigadores. Los conceptos, tipos y aplicaciones de las comunicaciones por satélite se han presentado en forma de tutorial. Los términos: órbitas de satélite, bandas de frecuencia, asignación de capacidad, propagación de señales de radio y comunicaciones láser se han descrito brevemente. Se han presentado las ecuaciones matemáticas para evaluar el efecto de la altura de la órbita en el período de tiempo y la relación entre la potencia disponible en la entrada de la antena receptora y la potencia de salida en la antena transmisora. Se ha presentado una breve reseña de las actividades de investigación recientes en las comunicaciones por satélite. Se espera que el documento sea útil para los nuevos participantes en el campo, y también para aquellos involucrados en el diseño y desarrollo de los nuevos sistemas.

Palabras clave: Comunicaciones por satélite, bandas de frecuencia y comunicaciones por láser.

I. INTRODUCTION

The term communication satellite refers to an artificial satellite put into space in a well defined orbit, for the purpose of telecommunications. The modern communications satellite are very advance indeed, and use various types of orbits including geostationary orbits, elliptical orbits and low polar and non polar Earth orbits. The interest in this field has grown tremendously [1, 2, 3, 4, 5] during the first decade in this century. Recently, Chopra [6] has discussed various types of the satellites and the global positioning system, which is a global radio navigation system, formed by a group of 24 satellites.

A satellite is just a self-contained communications system, which is able to receive signals from the Earth and transmit them back by using a transponder, which is in the form of an integrated receiver and transmitter for the radio signals. A satellite has three requirements –(i) withstanding the shock of a launch into orbit at ~ 28,000 km per, (ii) withstanding a hostile space environment, where it is subjected to radiation and extreme temperatures for its operational life ~ 20 years, and (iii) .being lightweight, since the cost of it is quite high, and is directly proportional to weight. These challenges are met by making an optimized design, and choosing light and durable materials. In addition, they must be reliable of operation in the vacuum of the space, with negligible maintenance and repair. Satellites based on the microwave radio relay technology are used for the fixed i.e. point to point services, i.e. Fixed Service Satellites (FSS). Other satellites are; Broadcast Service Satellites (BSS) or Direct Broadcast Service e.g. Satellite Television/Radio; and Mobile Service Satellites (MSS) e.g. Satellite Phones.

The other important uses of this technology are: communications to ships, vehicles, and planes, and for TV and radio broadcasting. Actually, two stations use a satellite as a relay station for their communication, when they are far away for using the conventional means for communicating through radio waves. Sending of the transmission to the satellite is called an uplink, and its conversion and sending to another earth station through the satellite transponder, is called a downlink. The satellite communication has many advantages over terrestrial communication. The satellite communication is very useful in remote area since it covers the long distance transmissions, being very powerful in sending and receiving the signals. The satellite communication services are very useful for the department of defence, where the soldiers on the fields are not able to use the wired services every time. Also, their missions and secrets can be kept undisclosed due to the national security reasons. Since the satellite communication is wireless, and working through the signals from the satellites, this service is always successful and hence very useful during the time of the natural disasters. The satellite communication gives the information about the weather, which helps in predicting the occurrence of the natural disaster. The Satellite communication services include a wide range of services like voice calling, video calling, radio, television channels, internet, and fax, which have become very important part of the commercial and corporate sectors. The satellite communication services are very beneficial and available at very reasonable cost to the customers anywhere, anytime and for any purpose they desire. The satellite communication services have led to the development of the different technologies like LCD and LED television sets. There are many additional advantages like: Mobile/Wireless Communication, independent of location, Wide area coverage, Wide bandwidth available throughout, very precise satellite to satellite communication, Independence from terrestrial infrastructure, Rapid installation of ground network, Uniform service characteristics, Total service from a single provider, and Small Fading margin (3dB). However, there are certain disadvantages like – very costly launching of satellites into the orbits, gradually reducing satellite bandwidth, short life time of ~ 20 years, redundancy in component, and a comparatively larger propagation delay.

II. TYPES OF SATELLITES

There are many types of satellites depending upon the Satellite Orbits (6) i.e. the orbits in which they are moving. These are: (i) Geostationary Earth Orbit (GEO), (ii) Low Earth Orbit (LEO), (iii) Medium Earth Orbit (MEO), and (iv) Other Orbits like - Molniya Orbit Satellites, and High Altitude Platform (HAP). These are briefly discussed below:

(i) GEOSTATIONARY EARTH ORBIT (GEO) The satellites belonging to this category are in the orbit at a height of 35,863 km above the earth, and in a direction along the equator. Objects in this orbit revolve around the earth at the speed equal to that of the earth rotation, which implies that the GEO satellites occupy the same position w.r.t. the earth. There are many advantages of these satellites: large coverage area (~ 25% of the earth's area), 24 hour view of a specific area, and hence are ideal for the satellite broadcast and other multipoint applications. However, there are certain disadvantages like - comparatively weak signal and a time delay in the signal, which is quite bad for the case of the point to point communication.

(ii) LOW EARTH ORBIT (LEO) The LEO satellites are much closer to the earth than GEO satellites, and are generally at the height of ~ 1,500 km above the earth, and continuously go on changing their position relative to the surface, and are visible for ~ 15-20 minutes during each pass. These satellites are useful, only if a network of such satellites is available. These satellites are closer to the earth, and, therefore, have better signal strength, and lesser time delay, resulting in their better suitability for the point to point communication. However, they have the disadvantages like – requirement of the costly network, compensation for the Doppler shifts caused by their relative movement, and the gradual orbital deterioration, due to the atmospheric drag effects.

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(iii) MEDIUM EARTH ORBIT (MEO) The MEO satellites are in the orbit in the range of 8,000 km -18,000 km above the earth. Though these satellites function in a manner similar to the LEO satellites, they are visible for much longer periods ~ 2 - 8 hours, and also have a larger coverage area than the LEO satellites. The advantages in this class of satellites is that because of the longer duration of visibility and wider coverage area, fewer satellites are needed in a MEO network than required in a LEO network, though the disadvantage is that the larger distance leads to a longer time delay and weaker signal than a LEO satellite.

(iv) MOLNIYA ORBIT SATELLITES (MOSs) The Molniya Orbit Satellite moves in elliptical orbit, and remains in a nearly fixed position w.r.t. to the earth for eight hours. They can be used in near polar regions, and series of three Molniya satellites can act like a GEO satellite.

(v) HIGH ALTITUDE PLATFORM SATELLITES (HAPSs) These are the new addition to the types of satellites. They are very close to the ground (r ~ 20km), and so cover a small area, and give a strong signal. Obviously, they are much cheaper to be put in position, though they require a large number of them for making a network.

(vi) SATELLITE ORBITS – EFFECT OF HEIGHT OF THE ORBIT ON THE TIME PERIOD The satellites, in general, move in circular orbits, each being a characteristic of the satellite, matched to the capability and objective of the sensor carried by it. The orbits are different in terms of the altitude, orientation and rotation of the satellites w.r.t. the Earth. The circular orbits are determined by equating the centripetal acceleration to the gravitational force. For a circular satellite orbit around a spherically homogenous planet, the gravitational force F_g and centrifugal force F_c balance each other, and are given by the simple laws of mechanics as:

$$F_g = mg(R/r)^2, \qquad (1),$$

and

$$F_c = mv^2 / r = m.(\omega^2).r \qquad (2)$$

where *m* is the : mass of satellite, *r* is the orbit radius (the orbit height being *h*), *v* is the speed, *ω* is the angular velocity, given by: *ω* = *v/r* , *g* is the gravitational constant (9/81m/s for the earth), and R is the radius of the planet (6380km for the earth) around which the satellite is revolving.

For the case of a circular orbit, these equations reduce to:

$$F_g = F_c = g(R/r)^2 = v^2 / r \qquad (3)$$

which implies:

$$v = [g(R)^2 / r]^{\frac{1}{2}} \qquad (4)$$

Thus, it is clear that v is independent of the satellite mass. The orbital period is given by:

$$T = 2\pi r / v = 2\pi r.[g(R)^2 / r]^{\frac{1}{2}} \qquad (5)$$

This equation shows that the time period increases with increase in r, i.e. height of the orbit. Though, a simple equation, it is really handy in fixing the initial parameters by the satellite designers.

(vii) FREQUENCY BANDS The satellite designers have to choose the frequency bands suitable for the different types of satellites. The various frequency bands in use are: L–Band: 1 - 2 GHz, used by MSS, S-Band: 2 - 4 GHz, used by Mobile Satellite Service (MSS), NASA, and deep space research, C-Band: 4 - 8 GHz, used by Fixed Satellite Service (FSS), X-Band: 8 - 12.5 GHz, used by FSS, Ku-Band: 12.5 - 18 GHz: used by FSS and Direct Broadcast Satellite (DBS), K-Band: 18 - 26.5 GHz: used by FSS and BSS, and Ka-Band: 26.5 - 40 GHz: used by FSS.

(viii) CAPACITY ALLOCATION Satellite frequency is broken into bands, and then further split into smaller channels in Frequency Division Multiple Accesses (FDMA). This helps in increasing the overall bandwidth within a frequency band due to the frequency reuse i.e. using a frequency by two carriers with orthogonal polarization. The number of sub-channels is limited by three factors: (i) Thermal noise , since a very weak signal is affected by the background noise., (ii) Intermodulation noise , since a very strong signal causes its own noise, and (iii) Crosstalk caused by excessive frequency reusing, is a serious source of disturbance, which has to be removed by the proper designing. There are two ways of performing the FDMA: (i) Fixed assignment multiple access (FAMA), in which the sub channel assignments are of a fixed allotment., and is considered as ideal for the broadcast satellite communication; (ii) Demand assignment multiple access (DAMA), in which the sub channel allotment is changed depending on demand, and is found as ideal for point to point communication.

The other type of splitting into smaller channels is the Time Division Multiple Access (TDMA), in which the transmission is broken into multiple time slots, each corresponding to a different transmitter. TDMA is being very commonly employed in the satellite communication, and is performed in the same ways as FDMA. This is because of the various factors: Digital equipment used in TDMA is much cheaper, possibility of the error correction, and increased efficiency due to the lack of intermodulation noise.

(ix) DIRECT BROADCAST SATELLITE (DBS) Direct Broadcast Satellite means Television Service or Satellites which deliver service. This is based on using Mini dish systems, equipped with parabolic surface that focuses the incoming signals into Feed Horn, which in turn reflects the outgoing signals into narrow beam. Its main part consists of Low Noise Blockdown Converter (LNB), and the system operates in upper Ku Band (12 GHz - 14 GHz). It requires the proprietary equipment, along with Encryption and Smart Card.

(x) FIXED SATELLITE SERVICE (FSS) Fixed Satellite Service operates in C-Band (3.4 GHz - 7 GHz). It requires geostationary satellite, 18 x 20 in elliptical dish, access cards, and MPEG-II compression e.g. from 270 Mbps down to 10 Mbps.

(xi) SATELLITE RADIO The Satellite Radio, in the form of the Digital Audio Radio Service (DARS), operates in S-Band (2.3 GHz), with 4 Second Delay. The others in this category are: XM and Sirius (in North America), and WorldSpace (in Europe, Middle East, Africa).

(xii) XM RADIO/ SIRIUS RADIO In the XM Radio category, two geostationary satellites (XM Rhythm at 115° west and XM Blues at 85° west), have replaced the previous XM Rock and XM Roll, and use 12.5 MHz of S band: 2332.5 to 2345.0 MHz. The SIRIUS Radio uses three medium earth orbit satellites, with extremely elliptical path.

(xiii) THE FUTURE SCENARIO OF THE SATELLITE COMMUNICATIONS There are many changes being brought in the satellite communication, in terms of the types of orbits, and their operation. The types of orbits being tried by some satellites are: (i) Geosynchronous, which have the same rotational velocity as earth, and maintain the position relative to earth. These are at a height of 35 786 km, and move with a velocity of 11 300 km/hr. (ii) Asynchronous, which are at much lower altitude, and have much higher velocity. Interestingly, they are constantly changing their position over the earth. The operations of these satellites are: Transmission, Reception, Low Noise Converter, Polarization, Tuner, and Antennas.

(xiv) SIGNAL PROPAGATION We discuss the radio signal propagation, which is based on the Free Space Propagation Model, which assumes that there is no obstruction in the line of sight, and is based on the Friis transmission equation being used in telecommunications engineering, for calculating the power received by one antenna under idealized conditions, when another antenna, at some distance away, is transmitting a known amount of power with no obstructions. The Friis free space equation, in its simplest form, is given by:

$$(P_r / P_t) = G_t.G_r(\lambda / 4\pi R)^2 \tag{6}$$

where P_r is the power available at the input of the receiving antenna, P_t is the output power to the transmitting antenna, G_t and G_r are respectively the antenna gains (with respect to an isotropic radiator) of the transmitting and receiving antennas, λ is the wavelength, and R is the distance between the antennas. The inverse of the factor in the bracket (i.e. $\lambda/4\pi R$) is the free-space path loss. If the gain is considered in the units of dB, the equation is slightly modified as:

$$P_r = P_t + G_t. + G_r + 20\ln(\lambda / 4\pi R) \tag{7}$$

where the gain has units of *dB*, and power has units of *dBm* or *dBW*. It has to be noted that the equation [6] is valid, when many conditions hold good: (i) $R >> \lambda$, since for $R < \lambda$, the equation gives the result that the received power is greater than the transmitted power, which is not possible on the basis of the law of conservation of energy; (ii) The antennas are in free space and without any obstruction, and without any multipath; (iii) Power at the output of the antenna is fully delivered into the transmission line, i.e. the antenna and transmission line are conjugate matched; (iv) The antennas are properly aligned and polarized; and (v) The bandwidth is so narrow that we can assume a single value for the wavelength.

It has to be noted that the ideal conditions are never observed in ordinary terrestrial communications, as there are obstructions, reflections from buildings, and also from the ground. The equation is reasonably accurate when there is negligible atmospheric absorption, or in case when the anechoic chambers are designed to minimize reflections.

If the effects of impedance mismatch, misalignment of the antenna pointing and polarization, and absorption are taken into account, the equation is modified as given below:

$$(P_r / P_t) = G_{tt}(\theta_t, \Phi_t).G_t r(\theta_{tr}\Phi_r).(\lambda / 4\pi R)^2 \\ (1-|\acute{\Gamma}_t|).(1-|\acute{\Gamma}_r|).\left[a_{ta_r} a_{ra_r}\right]^2 e^{(-\alpha R)} \tag{8}$$

where $G_t(\theta_t, \Phi_t)$ is the gain of the transmitting antenna in the direction (θ_t, Φ_t) in which it sees the receiving antenna., $G_r(\theta_r,\Phi_r)$ is the gain of the receiving antenna in the direction (θ_t,Φ_t) in which it sees the transmitting antenna, $\acute{\Gamma}_t$ and $\acute{\Gamma}_r$ are respectively the reflection coefficients of the transmitting and receiving antennas, at and ar are respectively the polarization vectors of the transmitting and receiving antennas, taken in the corresponding directions, and α is the absorption coefficient of the medium through which the signal is traveling.

In general, there are strong multipath (Path Loss is due to the fading of electromagnetic signal or the positive difference between the received power and the transmitted power in *dB*) effects or the line of sight is not free from an obstruction, and hence, the average value of the (P_r/P_t) is taken as:

$$(P_r / P_t)\alpha G_{tG_r}(\lambda.R)^n \tag{9}$$

where n has to be experimentally determined, and is found to be in the range of 3 - 5, and G_t and G_r and are respectively the mean effective gains of the transmitting and receiving antennas.

(xv) SPREAD SPECTRUM TECHNIQUES Spread Spectrum Techniques are useful in the telecommunication and radio communication, by which a signal (e.g. an electrical, EM, or acoustic) generated with a particular bandwidth is spread in the frequency domain, which results in a signal with a wider bandwidth, the techniques being used for many applications like – security in the communications, increasing resistance to the natural interference, noise and jamming, preventing the detection, and limiting the power flux density, which is useful in the satellite downlinks. The technique is based on transmitting the signal on a bandwidth considerably larger than the frequency content of the original information. The Frequency hopping is a basic modulation technique, used in spread spectrum signal transmission.

A signal structuring technique employing the direct sequence, frequency hopping, or a hybrid of these, is used for multiple access and multiple functions, which reduces the potential interference to other receivers, and also achieves privacy for the secure communication. Spread spectrum uses a sequential noise like signal structure to spread the normally narrowband information signal over a relatively wideband of frequencies, and the original information signal is retrieved by the receiver by correlating the received signals.

III. LASER COMMUNICATIONS

Recently, lasers have become very popular for communication purposes because of various advantages like- frequencies 7 – 8 times higher, larger bandwidth, smaller beam divergence, smaller antennas, and higher data rates. All these advantages are the result of the peculiar nature of laser radiation, being monochromatic and coherent beam of light. Different types of lasers have been tried for the communication, but the most suitable has been found to be Neodymium: yttrium, aluminum, garnet (Nd:YAG), that is a rod of crystalline YAG lightly doped with Nd used as the amplifier. In this case, the optical energy excites Nd atoms to higher energy state, which on returning to the normal energy state result in the emission of the light energy at the wavelength of 1.664 um. The communication is driven by modulation, for which the birefringence modulator has been found to be the most suitable. The system uses the electric field induced birefringence of the crystal for the rotation of the polarized light, which is caused by the modulated phase shift, just as the quarter wave plate introduces the static phase shift. The receivers i.e. the optical detectors convert the laser energy into an electric current. The system is based on the photon wave theory of light, according to which, the photons have some momentum that exerts a force on the receiver resulting in freeing the electrons (photoelectrons – the electrons resulting from the incidence of the light energy) from atoms of cathode, which are attracted to the anode, creating an electric current. There are two types of modulation (i) Optical Modulation Formats; and (ii) Pulse Interval Modulation. The first type is based on using the short energy pulses with a high peak power and low duty cycle, the pulses being of three types - Pulse Gated Binary Modulation (PGBM), Pulse Polarization Binary Modulation (PPBM), and Pulse Interval Modulation (PIM). The second type is the Pulse Interval Modulation, which is the most efficient type of modulation. This has N separate time slots in pulse interval, and transmit log2(N) bits per pulse. Since the pulse is sent during one of these time slots, time slot is considered as the value of the word, which is translated in the form of the binary data. Slot width is the difference between the two consecutive slots - Nth and (N-1) th. The laser data pulse occupies one such slot width. For an example, if we take N = 64, then log2 (64) = 6 bits of data. If we consider the case, when the pulse occurs at the time slot 36, then the data is obviously given by 100100.

IV. CONCLUSIONS

Satellite communication is very useful in a number of fields like - providing trunk links for communication providers, private networks for corporations, and temporary communication systems in disasters management, because of many advantages including wide coverage, flexible network configuration, and anti-disaster capability. Also, the satellite communication using handheld mobile phones has recently become commonly available. Satellites have proved very important for modern communications, and the initially used radio frequency communication has now been replaced by the more suitable laser communication, which at present is being considered as the best choice for satellites. Though the satellites have a large accessibility around the world, fiber optics has been found to be even more useful because of possessing much greater capacity and speed potential. The efforts are being made to combine these two technologies together, though that requires the development of gateways capable of optimizing the inherent benefits of each, and also addressing the differences between the two, the major one being accommodating the delay due to the slower speeds by satellite, which results in the packets arriving at the fiber network to be dropped.

The interest in the subject, especially in the mobile and networking has grown at a tremendous rate, and many recent papers including [7-18] have appeared. Arndt et al [7] have discussed the State Modeling of the Land Mobile Propagation Channel for Dual-Satellite Systems. Moraitis et al [8] have studied the Capacity of a SIMO Land Mobile Satellite System at C-Band: Polarized and Depolarized Received Field. Al-Jazzar et al [9] have presented their results on the Enhancement of wireless positioning in outdoor suburban NLOS environment using hybrid-network-GPS systems. Christopoulos et al [10] have provided the Linear and nonlinear techniques for multibeam joint processing in satellite communications. Yang et al [11] have given the Residue Code Based Low Cost SEU-Tolerant FIR Filter Design for OBP Satellite Communication Systems. Arnau et al [12] have done the Performance study of multiuser interference mitigation schemes for hybrid broadband multibeam satellite architectures. Ogundele et al [13] have suggested a mathematical model of antenna look angles, which is based on the mathematical representations of the equations governing them. Pultarova [14] has discussed that the European Space Agency (ESA) has finished testing of an innovative laser communication platform that speeds up data transfer from orbiting satellites. Hand [15] has discussed that Europe has launched massive laser communications satellite that will relay data between different spots on the globe by using not only the radio waves in the crowded L-band frequency range, but also test a laser communication device which is expected to be really very useful for the space communications. Toyoshima *et al*. [16] have discussed that a transportable optical ground station has been developed for the site diversity purposes which is useful for increasing the accessibility between the terrestrial and satellite stations. Toyoshima [17] has discussed the trends in laser communications in space. Toyoshima et al [18] have described some optical communication demonstration experiments. In view of these recent developments, it is expected that the field of satellite communications is still evolving and progressing.

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