Multiple Access System

- Applications employ multiple-access systems to allow two or more Earth stations to simultaneously share the resources of the same transponder or frequency channel.
- These include the three familiar methods:
  - FDMA,
  - TDMA, and
  - CDMA.
- Another multiple access system called space division multiple access (SDMA) has been suggested in the past. In practice, SDMA is not really a multiple access method but rather a technique to reuse frequency spectrum through multiple spot beams on the satellite.
- Because every satellite provides some form of frequency reuse (cross-polarization being included), SDMA is an inherent feature in all applications.

Multiple Access System

- TDMA and FDMA require a degree of coordination among users:
  - FDMA users cannot transmit on the same frequency and
  - TDMA users can transmit on the same frequency but not at the same time.
- Capacity in either case can be calculated based on the total bandwidth and power available within the transponder or slice of a transponder.
- CDMA is unique in that multiple users transmit on the same frequency at the same time (and in the same beam or polarization).
- This is allowed because the transmissions use a different code either in terms of high-speed spreading sequence or frequency hopping sequence.

Multiple Access System

- The capacity of a CDMA network is not unlimited, however, because at some point the channel becomes overloaded by self-interference from the multiple users who occupy it.

- Furthermore, power level control is critical because a given CDMA carrier that is elevated in power will raise the noise level for all others carriers by a like amount.

Multiple Access System

- Multiple access is always required in networks that involve two-way communications among multiple Earth stations.
- The selection of the particular method depends heavily on the specific communication requirements, the types of Earth stations employed, and the experience base of the provider of the technology.
- All three methods are now used for digital communications because this is the basis of a majority of satellite networks.

Multiple Access System

- The digital form of a signal is easier to transmit and is less susceptible to the degrading effects of the noise, distortion from amplifiers and filters, and interference.
- Once in digital form, the information can be compressed to reduce the bit rate, and FEC is usually provided to reduce the required carrier power even further.
- The specific details of multiple access, modulation, and coding are often preselected as part of the application system and the equipment available on a commercial off-the-shelf (COTS) basis.

Multiple Access System

- The only significant analog application at this time is the transmission of cable TV and broadcast TV.
- These networks are undergoing a slow conversion to digital as well, which may in fact be complete within a few years.

FDMA

- Nearly every terrestrial or satellite radio communications system employs some form of FDMA to divide up the available spectrum.
- The areas where it has the strongest hold are in single channel per carrier (SCPC), intermediate data rate (IDR) links, voice telephone systems, VSAT data networks, and some video networking schemes.
- Any of these networks can operate alongside other networks within the same transponder.
- Users need only acquire the amount of bandwidth and power that they require to provide the needed connectivity and throughput.
- Also, equipment operation is simplified since no coordination is needed other than assuring that each Earth station remains on its assigned frequency and that power levels are properly regulated.
- However, inter-modulation distortion (IMD) present with multiple carriers in the same amplifier must be assessed and managed as well.

FDMA

- The satellite operator divides up the power and bandwidth of the transponder and sells off the capacity in attractively priced segments.
- Users pay for only the amount that they need. If the requirements increase, additional FDMA channels can be purchased.
- The IMD that FDMA produces within a transponder must be accounted for in the link budget; otherwise, service quality and capacity will degrade rapidly as users attempt to compensate by increasing uplink power further.
- The big advantage, however, is that each Earth station has its own independent frequency on which to operate.
- A bandwidth segment can be assigned to a particular network of users, who subdivide the spectrum further based on individual needs.
- Another feature, is to assign carrier frequencies when they are needed to satisfy a traffic requirement. This is the general class of demand assigned networks, also called demand-assigned multiple access (DAMA).
- In general, DAMA can be applied to all three multiple access schemes previously described; however, the term is most often associated with FDMA.

Time Division Multiple Access and ALOHA

- TDMA is a truly digital technology, requiring that all information be converted into bit streams or data packets before transmission to the satellite. (An analog form of TDMA is technically feasible but never reached the market due to the rapid acceptance of the digital form.)
- Contrary to most other communication technologies, TDMA started out as a high-speed system for large Earth stations.
- Systems that provided a total throughput of 60 to 250 Mbps were developed and fielded over the past 25 years.
- However, it is the low-rate TDMA systems, operating at less than 10 Mbps, which provide the foundation of most VSAT networks.
- As the cost and size of digital electronics came down, it became practical to build a TDMA Earth station into a compact package.

Time Division Multiple Access and ALOHA

- Lower speed means that less power and bandwidth need to be acquired (e.g., a fraction of a transponder will suffice) with the following benefits:
  - The uplink power from small terminals is reduced, saving on the cost of transmitters.
  - The network capacity and quantity of equipment can grow incrementally, as demand grows.

Time Division Multiple Access and ALOHA

- TDMA signals are restricted to assigned time slots and therefore must be transmitted in bursts.
- The time frame is periodic, allowing stations to transfer a continuous stream of information on average.
- Reference timing for start-of-frame is needed to synchronize the network and provide control and coordination information.
- This can be provided either as an initial burst transmitted by a reference Earth station, or on a continuous basis from a central hub.
- The Earth station equipment takes one or more continuous streams of data, stores them in a buffer memory, and then transfers the output toward the satellite in a burst at a higher compression speed.

Time Division Multiple Access and ALOHA

- At the receiving Earth station, bursts from Earth stations are received in sequence, selected for recovery if addressed for this station, and then spread back out in time in an output expansion buffer.
- It is vital that all bursts be synchronized to prevent overlap at the satellite; this is accomplished either with the synchronization burst (as shown) or externally using a separate carrier.
- Individual time slots may be pre-assigned to particular stations or provided as a reservation, with both actions under control by a master station.
- For traffic that requires consistent or constant timing (e.g., voice and TV), the time slots repeat at a constant rate.

Time Division Multiple Access and ALOHA

- Computer data and other forms of packetized information can use dynamic assignment of bursts in a scheme much like a DAMA network.
- There is an adaptation for data, called ALOHA, that uses burst transmission but eliminates the assignment function of a master control.
- ALOHA is a powerful technique for low cost data networks that need minimum response time. Throughput must be less than 20% if the bursts come from stations that are completely uncoordinated because there is the potential for time overlap (called a collision).

Time Division Multiple Access and ALOHA

- The most common implementation of ALOHA employs a hub station that receives all of these bursts and provides a positive acknowledgement to the sender if the particular burst is good.
- If the sending station does not receive acknowledgment within a set “time window,” the packet is re-sent after a randomly selected period is added to prevent another collision.
- This combined process of the window plus added random wait introduces time delay, but only in the case of a collision.
- Throughput greater than 20% brings a high percentage of collisions and resulting retransmissions, introducing delay that is unacceptable to the application.

Time Division Multiple Access and ALOHA

- An optimally and fully loaded TDMA network can achieve 90% throughput, the only reductions required for guard time between bursts and other burst overhead for synchronization and network management.
- The corresponding time delay is approximately equal to one-half of the frame time, which is proportional to the number of stations sharing the same channel.
- This is because each station must wait its turn to use the shared channel.
- ALOHA, on the other hand, allows stations to transmit immediately upon need. Time delay is minimum, except when you consider the effect of collisions and the resulting retransmission times.

Time Division Multiple Access and ALOHA

- TDMA is a good fit for all forms of digital communications and should be considered as one option during the design of a satellite application.
- The complexity of maintaining synchronization and control has been overcome through miniaturization of the electronics and by way of improvements in network management systems.
- With the rapid introduction of TDMA in terrestrial radio networks like the GSM standard, we will see greater economies of scale and corresponding price reductions in satellite TDMA equipment.

Code Division Multiple Access

- CDMA, also called spread spectrum communication, differs from FDMA and TDMA because it allows users to literally transmit on top of each other.
- This feature has allowed CDMA to gain attention in commercial satellite communication.
- It was originally developed for use in military satellite communication where its inherent anti-jam and security features are highly desirable.
- CDMA was adopted in cellular mobile telephone as an interference-tolerant communication technology that increases capacity above analog systems.

Code Division Multiple Access

- It has not been proven that CDMA is universally superior as this depends on the specific requirements.
- For example, an effective CDMA system requires contiguous bandwidth equal to at least the spread bandwidth.
- Two forms of CDMA are applied in practice:
  (1) direct sequence spread spectrum (DSSS) and
  (2) frequency hopping spread spectrum (FHSS).
- FHSS has been used by the OmniTracs and Eutel-Tracs mobile messaging systems for more than 10 years now, and only recently has it been applied in the consumer's commercial world in the form of the Bluetooth wireless LAN standard. However, most CDMA applications over commercial satellites employ DSSS (as do the cellular networks developed by Qualcomm).

Code Division Multiple Access

- Consider the following summary of the features of spread spectrum technology (whether DSSS or FHSS):
  - Simplified multiple access: no requirement for coordination among users;
  - Selective addressing capability if each station has a unique chip code sequence—provides authentication: alternatively, a common code may still perform the CDMA function adequately since the probability of stations happening to be in synch is approximately $1/n$;
  - Relative security from eavesdroppers: the low spread power and relatively fast direct sequence modulation by the pseudorandom code make detection difficult;
  - Interference rejection: the spread-spectrum receiver treats the other DSSS signals as thermal noise and suppresses narrowband interference.

Code Division Multiple Access

- A typical CDMA receiver must carry out the following functions in order to acquire the signal, maintain synchronization, and reliably recover the data:
  - Synchronization with the incoming code through the technique of correlation detection;
  - De-spreading of the carrier;
  - Tracking the spreading signal to maintain synchronization;
  - Demodulation of the basic data stream;
  - Timing and bit detection;
  - Forward error correction to reduce the effective error rate;

Code Division Multiple Access

- The first three functions are needed to extract the signal from the clutter of noise and other signals.
- The processes of demodulation, bit timing and detection, and FEC are standard for a digital receiver, regardless of the multiple access method.

Multiple Access Summary

- The bottom line in multiple access is that there is no single system that provides a universal answer.
- FDMA, TDMA, and CDMA will each continue to have a place in building the applications of the future.
- They can all be applied to digital communications and satellite links.
- When a specific application is considered, it is recommended to perform the comparison to make the most intelligent selection.

Frequency Band Trade-Offs

- Satellite communication is a form of radio or wireless communication and therefore must compete with other existing and potential uses of the radio spectrum.
- During the initial 10 years of development of these applications, there appeared to be more or less ample bandwidth, limited only by what was physically or economically justified by the rather small and low powered satellites of the time.
- In later years, as satellites grew in capability, the allocation of spectrum has become a domestic and international battlefield as service providers fight among themselves, joined by their respective governments when the battle extends across borders.
- So, we must consider all of the factors when selecting a band for a particular application.

Frequency Band Trade-Offs

- The most attractive portion of the radio spectrum for satellite communication lies between 1 and 30 GHz.
- The relationship of frequency, bandwidth, and application are shown in Figure 2.9.
- The scale along the *x*-axis is logarithmic in order to show all of the satellite bands; however, observe that the bandwidth available for applications increases in real terms as one moves toward the right (i.e., frequencies above 3 GHz).
- Also, the precise amount of spectrum that is available for services in a given region or country is usually less than Figure 2.9 indicates.

Frequency Band Trade-Offs

- Letter band designations, frequency in Gigahertz:
  - L: 1.0–2.0;
  - S: 2.0–4.0;
  - C: 4.0–8.0;
  - X: 8–12;
  - Ku: 12–18;
  - Ka: 18–40;
  - Q: 40–60;
  - V: 60–75;
  - W: 75–110.

L-Band

- While there is effectively no rain attenuation at L-band, the ionosphere does introduce a source of significant link degradation.
- This is in the form of rapid fading called ionospheric scintillation, which is the result of the RF signal being split into two parts:
  - The direct path and
  - a refracted (or bent) path.
- At the receiving station, the two signals combine with random phase sometime resulting in the cancellation of signals, producing a deep fade.
- Ionospheric scintillation is most pronounced in equatorial regions and around the equinoxes (March and September).
- Both ionospheric scintillation and Faraday rotation decrease as frequency increases and are nearly negligible at Ku-band and higher.
- Transmissions at UHF are potentially more seriously impaired and for that reason, and additional fade margin over and above that at L-band may be required.

Polarization

- Polarization is the property of electromagnetic waves that describes the direction of the transverse electric field.
- Since electromagnetic waves consist of an electric and a magnetic field vibrating at right angles to each other.
- it is necessary to adopt a convention to determine the polarization of the signal.
- Conventionally, the magnetic field is ignored and the plane of the electric field is used.

L-Band

- From an overall standpoint, L-band represents a regulatory challenge but not a technical one.
- There are more users and uses for this spectrum than there is spectrum to use.
- Over time, technology will improve spectrum efficiency.
- Techniques like digital speech compression and bandwidth efficient modulation may improve the utilization of this very attractive piece of spectrum.
- The business failure of LEO systems like Iridium and Globalstar had raised some doubts that L-band spectrum could be increased.
- One could argue that more profitable land-based mobile radio services (e.g., cellular and wireless data services) could end up winning over some of the L-band.
- This will require never-ending vigilance from the satellite community.

S-Band

- S-band was adopted early for space communications by NASA and other governmental space research activities around the world.
- It has an inherently low background noise level and suffers less from ionospheric effects than L-band.
- DTH systems at S-band were operated in past years for experiments by NASA and as operational services by the Indian Space Research Organization and in Indonesia.
- More recently, the ITU allocated a segment of S-band for MSS and Digital Audio Radio (DAR) broadcasting.
- These applications hold the greatest prospect for expanded commercial use on a global basis.

S-Band

- As a result of a spectrum auction, two companies were granted licenses by the FCC and subsequently went into service in 2001–2002.
- S-band spectrum in the range of 2,320 to 2,345 MHz is shared equally between the current operators, XM Radio and Sirius Satellite Radio.
- A matching uplink to the operating satellites was assigned in the 7,025- to 7,075-MHz bands.
- Both operators installed terrestrial repeaters that fill dead spots within urban areas.
- With an EIRP of nominally 68 dBW, these broadcast satellites can deliver compressed digital audio to vehicular terminals with low gain antennas.

S-Band

- As a higher frequency band than L-band, it will suffer from somewhat greater (although still low) atmospheric loss and less ability to adapt to local terrain.
- LEO and MEO satellites are probably a good match to S-band since the path loss is inherently less than for GEO satellites.
- One can always compensate with greater power on the satellite, a technique used very effectively at Ku-band.

C-Band

- Once viewed as obsolete, C-band remains the most heavily developed and used piece of the satellite spectrum.
- During recent World Radio-communication Conferences, the ITU increased the available uplink and downlink bandwidth from the original allocation of 500 to 800 MHz.
- This spectrum is effectively multiplied by a factor of two with dual polarization.
- Further reuse by a factor of between two and five takes advantage of the geographic separation of land coverage areas.
- The total usable C-band spectrum bandwidth is therefore in the range of 568 GHz to 1.44 THz, which compares well with land-based fiber optic systems.
- The added benefit of this bandwidth is that it can be delivered across an entire country or ocean region.

C-Band

- Even though this represents a lot of capacity, there are situations in certain regions where additional satellites are not easily accommodated.
- In North America, there are more than 35 C-band satellites in operation across a 70° orbital arc.
- This is the environment that led the FCC in 1985 to adopt the radical (but necessary) policy of 2° spacing.
- The GEO orbit segments in Western Europe and east Asia are becoming just as crowded as more countries launch satellites.
- European governments mandated the use of Ku-band for domestic satellite communications, delaying somewhat the day of reckoning.
- Asian and African countries favor C-band because of reduced rain attenuation as compared to Ku- and Ka-bands, making C-band slots a vital issue in that region.

C-Band

- C-band is a good compromise between radio propagation characteristics and available bandwidth.
- Service characteristics are excellent because of the modest amount of fading from rain and ionospheric scintillation.
- The one drawback is the somewhat large size of Earth station antenna that must be employed.
- The 2° spacing environment demands antenna diameters greater than 1m, and in fact 2.4m is more the norm.
- This size is also driven by the relatively low power of the satellite, itself the result of sharing with terrestrial microwave.
- High-power video carriers must generally be uplinked through antennas of between 7m and 13m; this assures an adequate signal and reduces the radiation into adjacent satellites and terrestrial receivers.

C-Band

- The prospects for C-band are good because of the rapid introduction of digital compression for video transmission.
- New C-band satellites with higher EIRP, more transponders, and better coverage are giving C-band new life in the wide expanse of developing regions such as Africa, Asia, and the Pacific.

X-Band

- Government and military users of satellite communication established their fixed applications at X-band.
- This is more by practice than international rule, as the ITU frequency allocations only indicate that the 8-GHz portion of the spectrum is designated for the FSS regardless of who operates the satellite.
- From a practical standpoint, X-band can provide service quality at par with C-band; however, commercial users will find equipment costs to be substantially higher due to the thinner market.
- Also, military-type Earth stations are inherently expensive due to the need for rugged design and secure operation.
- Some countries have filed for X-band as an expansion band, hoping to exploit it for commercial applications like VSAT networks and DTH services. As discussed previously, S-DARS in the United States employs X-band feeder uplinks.
- On the other hand, military usage still dominates for many fixed and mobile applications.

Ku-Band

- Ku-band spectrum allocations are somewhat more plentiful than C-band, comprising 750 MHz for FSS and another 800 MHz for the BSS. Again, we can use dual polarization and satellites positions 2° apart.
- Closer spacings are not feasible because users prefer to install yet smaller antennas, which have the same or wider beam-width than the correspondingly larger antennas for C-band service.
- Typically implemented by different satellites covering different regions, Ku regional shaped spot beams with geographic separation allow up to approximately 10X frequency reuse.
- This has the added benefit of elevating EIRP using modest transmit power;
- G/T likewise increases due to the use of spot beams.
- The maximum available Ku-band spectrum could therefore amount to more than 4 THz.

Ku-Band

- Exploiting the lack of frequency sharing and the application of higher power in space, digital DTH services from DIRECTV and EchoStar in North America ushered in the age of low-cost and user-friendly home satellite TV.
- The United Kingdom, continental Western Europe, Japan, and a variety of other Asian countries likewise enjoy the benefits of satellite DTH.
- As a result of these developments, Ku-band has become a household fixture (if not a household word).

Ku-Band

- The more progressive regulations at Ku-band also favor its use for two-way interactive services like voice and data communication.
- Low-cost VSAT networks typify this exploitation of the band and the regulations. Being above C-band, the Ku-band VSATs and DTH receivers must anticipate more rain attenuation.
- A decrease in capacity can be countered by increasing satellite EIRP.
- Also, improvements on modulation and forward error correction are making terminals smaller and more affordable for a wider range of uses.
- Thin route applications for telephony and data, benefit from the lack of terrestrial microwave radios, allowing VSATs to be placed in urban and suburban sites.

Ka-Band

- Ka-band spectrum is relatively abundant and therefore attractive for services that cannot find room at the lower frequencies.
- There is 2 GHz of uplink and downlink spectrum available on a worldwide basis.
- Conversely, with enough downlink EIRP, smaller antennas will still be compatible with 2° spacing.
- Another facet of Ka-band is that small spot beams can be generated onboard the satellite with achievable antenna apertures.
- The design of the satellite repeater is somewhat more complex in this band because of the need for cross connection and routing of information between beams.
- Consequently, there is considerable interest in the use of onboard processing to provide a degree of flexibility in matching satellite resources to network demands.

Ka-Band

- The Ka-band region of the spectrum is perhaps the last to be exploited for commercial satellite communications.
- Research organizations in the United States, Western Europe, and Japan have spent significant sums of money on experimental satellites and network application tests.

Ka-Band

- From a technical standpoint, Ka-band has many challenges, the biggest being the much greater attenuation for a given amount of rainfall (nominally by a factor of three to four, in decibel terms, for the same availability).
- This can, of course, be overcome by increasing the transmitted power or receiver sensitivity (e.g., antenna diameter) to gain link margin.
- Some other techniques that could be applied in addition to or in place of these include:
  (1) dynamic power control on the uplink and downlink,
  (2) reducing the data rate during rainfall,
  (3) transferring the transmission to a lower frequency such as Ku- or C-bands, and
  (4) using multiple-site diversity to sidestep heavy rain-cells.
- Consideration of Ka-band for an application will involve finding the most optimum combination of these techniques.

Ka-Band

- The popularity of broadband access to the Internet through DSL and cable modems has encouraged several organizations to consider Ka-band as an effective means to reach the individual subscriber.
- Ultra-small aperture terminals (USATs) capable of providing two-way high-speed data, in the range of 384 Kbps to 20 Mbps, are entirely feasible at Ka-band.
- Hughes Electronics filed with the FCC in 1993 for a two-satellite system called Spaceway that would support such low-cost terminals.
- In 1994, they extended this application to include up to an additional 15 satellites to extend the service worldwide.
- The timetable for Spaceway has been delayed several times since its intended introduction in 1999.
- While this sounds amazing, strong support from Craig McCaw, founder of McCaw Cellular (now part of AT&T Wireless), and Bill Gates (cofounder of Microsoft) lent apparent credibility to Teledesic.
- In 2001, Teledesic delayed introduction of the Ka-band LEO system. A further development occurred in 2003 when Craig McCaw bought a controlling interest in L/S-band non-GEO Globalstar system.

Ka-Band

- While the commercial segment has taken a breather on Ka-band, the same cannot be said of military users.
- The U.S. Navy installed a Ka-band repeater on some of their UHF Follow-On Satellites to provide a digital broadcast akin to the commercial DTH services at Ku-band.
- It is known as the Global Broadcast Service (GBS) and provides a broadband delivery system for video and other content to ships and land-based terminals.
- In 2001, the U.S. Air Force purchased three X- and Ka-band satellites from Boeing Satellite Systems.
- These will expand the Ka-band capacity by about three on a global basis, in time to support a growth in the quantity and quality of Ka-band military terminals.
- The armed services, therefore, are providing the proving grounds for extensive use of this piece of the satellite spectrum.

Q and V-Bands

- Frequencies above 30 GHz are still considered to be experimental in nature, and as yet no organization has seen fit to exploit this region.
- This is because of the yet more intense rain attenuation and even atmospheric absorption that can be experienced on space-ground paths.
- Q- and V-bands are also a challenge in terms of the active and passive electronics onboard the satellite and within Earth stations.
- Dimensions are extremely small, amplifier efficiencies are low, and everything is more expensive to build and test.
- For these reasons, few have ventured into the regime, which is likely to be the story for some time.
- Perhaps one promising application is for ISLs, also called cross links, to connect GEO and possibly non-GEO satellites to each other.
- To date, the only commercial application of ISLs is for the Iridium system, and these employ Ka-band.

Laser Communications

- Optical wavelengths are useful on the ground for fiber optic systems and for limited use in line-of-sight transmission.
- Satellite developers have considered and experimented with lasers for ISL applications, since the size of aperture is considerably smaller than what would be required at microwave.
- On the other hand, laser links are more complex to use because of the small beam-widths involved.
- Control of pointing is extremely critical and the laser often must be mounted on its own control platform.
- In 2002, the European Space Agency demonstrated a laser ISL called SILEX, which was carried by the Artemis spacecraft.
- The developers of this equipment achieved everything that they intended in this government-funded program.

Summary of Spectrum Options

- The frequency bands just reviewed have been treated differently in terms of their developmental timelines (C-band first, Ka-band last) and applications (L-band for MSS and Ku band for BSS and DTH).
- However, the properties of the microwave link that relate to the link budget are the same.
- Of course, properties of different types of atmospheric losses and other impairments may vary to a significant degree.
- This requires a careful review of each of the terms in the link budget prior to making any selection or attempting to implement particular applications.