Optimum Tradeoffs for Millimeter Wave and Infrared Satellite Communication

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ABSTRACT
Satellite-ground tradeoffs are discussed for minimal cost satellite communication systems. Lossy millimeter wave systems are introduced with Wilson's sun tracker data. Frequencies in the 40-47 and 95-100 GHz regions are found to be attractive. Loss comparisons with optical systems may be found with Chu and Hogg's analysis, and Chan's observation allow economic comparisons of millimeter wave and optical systems.

1. Background for Comparison of Millimeter Wave and 10 Micron Satellite Systems

V. Chan (1) has pointed out that optical intersatellite communications links have clear size and cost advantages over millimeter wave links. However, optical links have not been extensively considered as reasonable satellite-ground links because of cloud, rain and atmospheric attenuation. With the aid of Chu and Hogg (2), it is possible to compare the losses and the optimum tradeoffs between millimeter wave and 10 micron satellite communications systems.

Satellite communication systems require intensive investment in both the space segment and the ground segment. A careful balance is required between the two segments in order to meet the demands of the link equation. The link equation could be satisfied with large spacecraft and small ground sites, or conversely with small spacecraft and large ground sites as was done in the '60s. One may ask whether there is an optimum tradeoff possible between the two, and if so whether the results may be expressed concisely.

Thomas Teichmann addressed this problem in the fertile research period of the 1960-1961 time period (3). He recognized that cost of ground stations was strongly related to size, and that spacecraft cost was related to mass and size of antenna systems. The total cost of the system could then be written while including the necessity of the link equation. Then, the partials of cost per bit could be taken with respect to ground size and satellite size simultaneously in two separate equations. These equations were equated to zero, and optimum ground and spacecraft sizes were found. The results also implied optimum cost relations between the space and ground segments. When the spacecraft carried a directional antenna, two thirds of the size dependent system cost was to be appropriated to the spacecraft. The results also included a free space loss term.

We extend the Teichmann free space loss term to include atmospheric loss. Gaseous attenuation is the first part to be considered, with special care for the oxygen resonance lines so that millimeter wave bands from 30-50 GHz and 95-100 GHz can be compared. A modified Crane rain attenuation model is then added. The rain model is modified with Wilson's (4) rain exponent which is suitable through 90 GHz. Rain is a probabilistic process, and it is necessary to modify the deterministic Teichmann tradeoff analysis. Rather than minimizing the cost per information bit, one may use a Bayes strategy (5) of minimizing the expected cost per bit. Chu and Hogg show cloud losses for 10 micron systems. The advantages of infrared systems are discussed for light cloud losses, and a crossover point of millimeter wave systems for heavy cloud losses concludes the paper.

Figure 1-1 outlines the background of the Teichmann analysis. A downlink limited communication link may be satisfied with an adequate combination of satellite transmitter (Pt), satellite antenna (At), and ground receiver (Ar). The downlink requires a critical product of the three variables, as shown by a simple equation, which can be generated with the aid of unusual units:

\[ P_R = P_t A_R A_t f^2 / r^2 \]
where: \( f \) = carrier frequency (GHz)  
\( r \) = separation distance (ft)  
\( A_R \) = receiving antenna area (ft\(^2\))  
\( A_t \) = transmitting antenna area (ft\(^2\))

However, Teichmann recognized that system economics varies in an entirely different way. He postulated that ground system cost was proportional to antenna size, and this was later confirmed by Pope across a large range of frequencies which extended into the millimeter wave region. He also recognized that space costs were strongly dependent on satellite mass and the ability of launch vehicles to deliver large satellite mass at low cost.

Optimum ground and space segment sizes may be found which minimize total system cost. When the ground station and satellite are varied against each other while maintaining the necessary link equation, the optimum ground station antenna system cost turns out to be the same as the optimum satellite antenna system cost. Figure 1-2 illustrates the system cost, relative to an optimum tradeoff, for varying ground antenna size. Note that a quadrupling of the ground antenna size implies a doubling of total system cost. Launch costs are left totally general for Figure 1-1, but system costs for different launch costs are compared in Figure 1-3 for 10\(^5\) $/lb and 10\(^4\) $/lb. Only a factor of 10\(^{(2/3)}\) exists for the ratio of system costs because ground and satellite system costs are asked to compensate for each other's weaknesses during the optimization.
2. ATMOSPHERIC ATTENUATION

The Bell Labs suntracker experiments of the late '60s offered a rare opportunity to observe a wide range of frequencies simultaneously across a full range of weather conditions. The attenuation statistics can be used, at a given frequency such as 16 GHz, to construct or verify rain attenuation models. Wilson went further, however, and established correlation between attenuation over a significant part of the millimeter wave region between 30 - 90 GHz. He found that rain attenuation (dB) was typically proportional to $r^{(1.8)}$. The rain attenuation statistics may be represented as Figure 2-1. Attenuation is also a function of elevation angle. Optimum frequencies for variable elevation system may be found with the aid of the Appendix.

Total atmospheric attenuation is used here as the sum of gaseous and rain attenuations. A Teichmann analysis would compensate the atmospheric loss optimally by sizing the key ground station and satellite sizes as proportional to (power loss)$^{(1/3)}$. This would imply that expected cost per information bit (Appendix) may be described for a Teichmann analysis over a wide range of frequencies. Figure 2-3 indicates relative expected cost/bit vs. frequency. Three attractive regions appear at 17, 30-40, and 90 GHz. Of course, communication systems typically require reasonable reliability and objections to the higher bands may be justified on the basis of reliability. Figure 2-4 includes a second ground station for independent reception, and the system costs shift upward. The higher bands are seen to remain attractive. Optimum frequencies for variable elevation systems are discussed in the appendix.

Gaseous attenuation is also important in the millimeter region. Convenient forms for gaseous attenuation were found (4, 5) for both oxygen and water vapor attenuation which allow representations as Figure 2-2. The small water vapor resonance at 22 GHz and an overwhelming oxygen resonance at 60 GHz are clearly identifiable.

The millimeter wave band may be especially attractive for aircraft. Attenuation drops, and reliability increases for aircraft at 10,000 feet as in Figure 2-5.
System Cost may also be presented as a 3D plot, as Figure 2-6. The optimum receiver size in the plot is at AR = 1, where AR is relative to optimum size.
3. FOG AND RAIN AT LASER FREQUENCIES

Chu and Hogg have implied the intrinsic frequency diversity benefits in their insightful 1968 article. Rain attenuation actually drops as frequency increases from 90 GHz to the 300 THz (1 micron) region. This may be seen in Fig. 3-1. Cloud attenuation increases dramatically, however. A dense fog may be seen to offer 70 dB/km Gr at 10 microns wavelength.

![Chu's Rain and Heavy Fog Att'n vs. F, GHZ](image)

**Figure 3-1: Chu and Hogg's Fog Attenuation (top) vs. Frequency (note 10μ at 30,000 GHz)**

A dramatic fog attenuation at 10 microns would at first appear to disqualify laser communication for any cloudy areas until the size advantages of Chan are included. He has pointed out that 8" lasers offer the performance of 8' 60 GHz intersatellite links. This amounts to a 21 dB laser advantage at a given size and cost. A comparison of the 70 dB loss/km with the laser gain advantage reveals the possibility that 10 micron radiation for satellite-ground communication would be competitive with millimeter waves for clouds less than 300 meters thick.

CONCLUSION

Optimal system tradeoffs allowed excess atmospheric losses for millimeter wave systems to be compensated, so that system costs increased slowly as (loss)\(^{1/3}\). The 30-47 GHz and 90 GHz regions were attractive. Optical systems at 10μ wavelength were also suggested to be competitive for cloud layers less than 300m.

REFERENCES


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APPENDIX

A Method for Optimum Frequency Selection in a Variable Elevation System

A fixed elevation angle system allows convenient conceptual results to be found for optimum frequencies. Fixed elevation attenuation may be represented as nearly monotonically increasing throughout the 10-50 GHz region. Net loss for fixed size (fixed cost) parabolic antennas may be generated with the aid of:

\[ \text{Net Loss} = \text{Atmospheric Loss} - 20 \log_{10}(F) \]

and optimum frequencies for minimum net loss may be found.

If, however, satellite elevation is a continuous variable, one may be forced to deal with a more general net loss function. A net loss function for Region D (Washington, DC) may be represented as Eq. A-1 and Fig. A-1.

\[ \text{Eq. A-1: Net Loss Function for Region D (Washington DC)} \]

\[ \text{Out[2]} = 115.033 \cdot 0.89422 \cdot \text{EL} + 0.0239618 \cdot \text{EL}^2 + 0.0000257479 \cdot \text{EL}^3 + 8.00353 \times 10^{-7} \cdot \text{EL}^4 - 10.9092 \cdot F - 0.00823157 \cdot \text{EL} \cdot F + 0.00156356 \cdot \text{EL}^2 \cdot F + 0.460541 \cdot F^2 - 0.000191151 \cdot \text{EL} \cdot F^2 - 0.00840928 \cdot F^3 + 0.00000590047 \cdot F^4 \]

\[ \text{Figure A-1: Net Loss Function for Region D (Washington DC)} \]
If a moving satellite system can be represented with nearly Gaussian elevation statistics, the net loss (A-1) may be integrated over the elevation probability density function with the aid of Mathematica (6) to yield a concise Fortran form as Eq. A-2. The new variables $MU$ and $SD$ refer to the mean and standard deviation of the elevation angle, respectively.

$$\begin{align*}
115.0325063696671 - 10.90917373063452*F + \\
- 0.4605412021296418*F^{*2} - \\
- 0.00840928522160635*F^{*3} + \\
- 0.00005900468270343147*F^{*4} - \\
- 0.89422028326723*MU - \\
- 0.00823157043631499*F*MU - \\
- 0.00001911510289312521*F^{*2}*MU + \\
- 0.02396176386113027*MU^{*2} + \\
- 0.0001563560027938568*F*MU^{*2} - \\
- 0.00002574789178750787*MU^{*3} + \\
- 8.00352742151892e-7*MU^{*4} + \\
- 0.0237823296642284*SD^{*2} + \\
- 0.000155185153210446*F*SD^{*2} - \\
- 0.0007666524729125351*MU*SD^{*2} + \\
- 4.766156499622808e-6*MU^{*2}*SD^{*2} + \\
- 2.117582368135751e-22*MU*SD^{*3} + \\
- 1.897103748200807e-6*SD^{*4}
\end{align*}$$

**Equation A-2:**

A dynamic system of Molniya satellites with average elevation near 55 degrees in the Northern temperate zone may be used as an example. Fig. A-2 indicates a locally minimum net loss (optimum frequency region) between 40-47 GHz.

![Integrated Molniya Net Loss Graph](image-url)