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An Economic Systems Analysis of Land Mobile Radio Telephone Services

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ABSTRACT

Expansion of land-mobile radio telephone service via the introduction of cellular technology in major urban areas is proceeding. Such systems provide for large user capacity, nationwide compatibility, and widespread availability without universal coverage. It has been proposed that universal coverage could be obtained by integrated combinations of cellular, trunked and satellite systems.

This paper deals with the economic interaction of the terrestrial and satellite systems. Parametric equations are formulated to allow examination of necessary user thresholds and growth rates as a function of system costs. Conversely, first order allowable systems costs are found as a function of user thresholds and growth rates. Transitions between satellite and terrestrial service systems are examined. User growth rate density (user/year/km^2) is shown to be a key parameter in the analysis of systems compatibility.

The concept of system design matching the price/demand curves is introduced and examples are given. The role of satellite systems are critically examined and the economic conditions necessary for the introduction of satellite service are identified.

INTRODUCTION

Expansion of land mobile phone communications services in the United States is currently beiung pursued by AT&T and the Radio Common Carriers (RCC's). AT&T and others are developing a cellular concept (1) for eventual use in major urban areas, suburbs, and principal road routes between metropolitan centers (1,2). Expansion of cellular service to rural areas will be slow (if it takes place at all) because user populations are generally insufficient to warrant the expense of cellular technology. In the interest of providing services that are compatible nationwide, it has been proposed that conventional "trunked" type service or satellite service be provided to low population density areas (3,4). Such systems may, in fact, be used to build user populations in areas not initially served by cellular means to levels economically justifying high technology service (3).

This paper deals with the economic interaction of terrestrial and space systems. The three land-mobile service systems mentioned above will be briefly described. Parametric equations will be formulated to allow examination of necessary user thresholds and growth rates as a function of systems cost. Conversely, allowable systems costs are found as a function of user thresholds and growth rates. Transition between terrestrial and space systems are examined.

SYSTEM DESCRIPTIONS

Only brief funtional descriptions of the three delivery systems will be presented to orient the reader. The systems are shown schematically in Figure 1.

Cellular System

In a mature cellular system, directional antennas are used at the base stations to serve three adjoining cells. The motivations for directional antennas is reduced co-channel interference from mobiles and base stations outside the service area. This, in turn, implies closer spacing of co-channel sites and cells and, thus, higher spectrum utilization or, conversely, fewer base station sites to serve a given traffic load. The base stations are linked to a Mobile Telephone Switching Office (MTSO) which controls the call switching and base station activities. The MTSO is, in turn, linked to the switched network via central offices or toll offices. A few of the allocated voice channels are used for set-up procedures. A mobile unit monitors one of the "set-up" channels (the strongest) when not in use. When the mobile unit is paged, it responds, receives a channel assignment, tunes to that channel, and alerts the operator. A similar set of procedures is followed when the mobile unit initiates a call.

Trunked System (3)

A "trunked" system compatible with the cellular systems would use a single transmitter for links to the mobile unit, but many remote receivers are used for links from the mobile. In this way, the mobile equipment is compatible with the low power cellular concept. Several functions necessary for cellular services are not required for trunked services. Zone change functions between receive cells, and localizing the mobile to a particular base station in a cell is not required. Although call set-up procedures are the same as described for the cellular system, fewer control channels are used since frequency diversity for control purposes is not required.

Satellite System [4,5,6,7]

Based on previous studies, the satellite land mobile system would use a multibeam antenna producing foot prints that are large compared to either the cellular or trunked terrestrial systems. For purposes of this paper, interference or signalling considerations will not be detailed. It is sufficient to indicate that: call set-up procedures are similar to the terrestrial system, mobile uplink and downlink frequencies are likely to be in the UHF band, and that RF to earth stations connected to the switched network can be at S, C, Ku or Ka-bands. Call routing within the satellite may take many forms. A simple system would be a single ground station per beam through which all calls to or from mobiles pass. A more complicated scheme may require earth stations for each area code and on-board switching to insure "single-hop" only calls to mobile units.

Capacities

Table I shows the relative capacity ranges for the three land mobile systems. The basic assumptions in generating the data are: 10 MHz bandwidth (for forward or return links to mobiles) or 333 duplex channels available in the spectrum; control and signalling channels are not considered; 33 or 63 telephone users per Erlang: 250 dispatch users per Erlang, and blocking probability of .02 during the busy hour under lost calls cleared situations. For the satellite system, it was also assumed: the foreshortened area of CONUS visible from geosynchronous orbit to be 7.5×10^6 km^2; and the maximum number of beams to be 100. The variation in satellite systems capacity is shown in Figure 2 as a function of the number of beams. The range 10 to 100 beams implies beamwidths from 1.25° to .39° and antenna diameters from 21.3m to 68.6m at 800 MHz. The satellite minimum capacity in Table 1 assumes a single CONUS beam.

The cellular system limits are derived from information contained in Reference 1. The trunked system limits are derived from information in Reference 3. While a single channel trunked system is possible, the investment cost per user is high and, thus, a single channel trunked system is not considered practical.

From Table 1, the range of user densities of the three systems shows potential compatibility. The upper user density of the satellite system overlaps the lower user density of the trunked system and the upper user density of the trunked system overlaps the lower user density of the cellular system.

SYSTEM ECONOMICS

In this section, the parametric equations to evaluate system economics are formulated.

Figure 3 depicts the total user charge consisting of three segments:

- A mobile unit charge
- A telephone connection charge (which may be unnecessary for dispatch service)
- A shared system charge for the "outside" plant such as towers, transmitters, receivers, switching, satellites, earth stations, etc., depending on which system is used.

Since the shared system is the major sink for capital, the following derivation concentrates on that investment. The basic shared system venture cash flow is shown in Figure 4. Let R be the equivalent lump sum investment in the shared system at time "0". Assume that an after tax return on that investment of i% per year is desired and no inflation is considered. Then, the following cost equations are derived for a system with a predicted life of t_0 years:

(1) $R(1+i)^{t_0} = \int_0^{t_0} P(t)dt$

where P(t) is the net after tax annual income.

Now:

(2) P(t) = Income - Taxes - Expenses

(3) Income = $I(t) = C_u N(t)$

where C_u is the annual charge per user and N(t) is the number of users at time t.

(4) Taxes = T(t) = (Income - depreciation - expenses) x tax rate

$$T(t) = \left[I(t) - D - E\right] \times TR$$

For simplicity, straight line depreciation is assumed, so that

(5) $D = \frac{R}{t_0}$ (dollars per year, a constant)

It is also assumed that annual expenses are a percentage of the investment.

(6) E = KR (dollars per year, a constant)

Thus, at a 50% tax rate, equation (1) becomes:

(7) $R(1+i)^{t_0} = \int_0^{t_0} C_u N(t)dt - \int_0^{t_0} KR\, dt - \int_0^{t_0} .5 \left[C_u N(t) - \frac{R}{t_0} - KR\right] dt$

Equation (7) may be integrated and terms collected.

(8) $R\left[(1+i)^{t_0} + .5Kt_0 - .5\right] =$

$.5\, C_u \int_0^{t_0} N(t)\, dt$

Let:

(9) $G = \frac{.5}{\left[(1+i)^{t_0} + .5Kt_0 - .5\right]}$

and write:

(10) $R = C_u G \int_0^{t_o} N(t)\, dt$

Equation (10) relates the allowed system investment, R, to the user charges for the shared system, C_u, the after-tax return on investment, i, the operating expense ratio, K, and the market statistics embodied in $\int_0^{t_o} N(t)dt$. Conversely, equation (10) also relates the required market ($\int Ndt$) given a system investment R. The term G is plotted in Figure 5 as a function of t_o, with i and K as parameters. At t_o = 5 years, G ranges from .25 to .55; at t_o = 10, G ranges from .11 to .37; at t_o = 15 years, G ranges from .055 to .26. An example of equation (10) is shown in Figure 6 for K = .1, i = 10%, t_o = 7 years.

While equation (10) is interesting in itself, another facet of economics must be considered in the analysis. Noting that there are economies of scale benefits in system design, the shared investment R may be expressed as:

(11) $R = R_B \left(\frac{C}{C_B}\right)^m$

where R_B - is some known base investment at some basic capacity C_B.

C - is the designed system capacity

m - is the exponent relating the expansion of the basic system.

(m < 1 for economy of scale)

Equations (10) and (11) may be used to find system design capacity given a market, or find the required market as a function of system design. From (10) and (11):

(12) $C = \left[\frac{C_B^m \; C_u \; G}{R_B} \int_0^{t_o} Ndt\right]^{1/m}$

or

(13) $\int_0^{t_o} Ndt = \frac{R_B}{C_u G} \left(\frac{C}{C_B}\right)^m$

There are limitation on the use of equations (12) and (13). Care must be taken in selecting the variables to insure a result consistent with input data.

To complete the discussions, it is apparent that expressing $\int Ndt$ as a function of system capacity is desirable. If the system is initially full, then:

(14) $\int_0^{t_o} Ndt = Ct_o$ (an upper bound)

Assuming a linear growth rate, if the system saturates before the end of design life, then:

(15) $\int_0^{t_o} Ndt = Ct_o - \frac{1}{2\dot{N}} (C-I_c)^2$

Where I_c is the initial number of users, and $\dot{N}$ is the rate of user increase. If the system does not saturate before the end of design life, then

(16) $\int_0^{t_o} Ndt = I_c t_o + \dot{N} \frac{t_o^2}{2}$

For the remaining analysis, assume

(17) $\int_0^{t_o} Ndt = A\, Ct_o$ where $0 < A < 1$

then from equation (13), we have:

(18) $(C_u G\, At_o)C = R_B \left(\frac{C}{C_B}\right)^m$

which can be solved for C

(19) $C = \left[\frac{R_B \; C_B^{-m}}{A\, C_u\, G\, t_o}\right]^{1/(1-m)}$

The variable A is the fraction of total system service capacity expressed in user-years.

The relationship of A to growth rate, $\dot{N}$, and capacity, C, is shown in Figure 7 for various initial conditions and t_o = 10 years.

For land mobile telephone service, equations (15) through (19), Figure 7, and system technical characteristics may be used to parametrically study the systems design process.

SYSTEM DESIGN

The system design process is related to market analysis as shown schematically in Figure 8. Market analysis produces price vs. demand curves and expected growth curves. Systems Design produces cost vs. system size curves at various rates of return and technology levels used. If market analysis and systems design were 100% accurate, the land-mobile radiotelephone service supplier would implement the system which closely matches the market demand curve at the highest possible rate of return. This is illustrated in Figure 9.

Because of uncertainty, system design can be considered a global optimization problem, or a tradeoff of conflicting desires. While many criteria must be considered, a few of the major ones are:

1. Maximize rate of return, i.

2. Minimize the required investment, thus minimizing the necessary system capacity.

3. System capacity should be large enough to provide "economy of scale" benefits.

4. Minimize user charges to capture the maximum number of customers, yet minimize the necessary user capture rate for system success.

Given the above criteria, the design process must proceed to answer the following two key questions:

1. Given an investment (i.e. system capacity), what size market must be served at a given user charge for a desired rate of return?

2. Given market characteristics (size, rate of growth) at any given user charge, what size system is consistent with that market at a desired rate of return?

LAND MOBILE SYSTEMS

Satellite System

Figure 10 shows the use of equation (19) to find values of C (capacity) as a function of shared system user charge, C_u. It was assumed that: M = .6; R_B = \$50M for C_B = 20,000 users; and t_o = 10 years. The fraction of service capacity, A, and the term G are parameters. The figure is scalable for different assumptions for R_B.

All curves move "up" by a factor of 2.75 if R_B = \$75M. Also shown in Figure 10 are the capacities of single beam, 10 beam, and 100 beam satellite systems (from Figure 2). In addition, the figure shows lines of constant user service capacity for G = .37 and under the assumption of no initial users (I_c = 0).

Figure 10 may be used to address the question of market size given a system capacity (investment).

Example:

Consider a 10-beam satellite system with a capacity of ~60K users and a lifetime of 10 years. From equation (11) and the assumption for Figure 10, such a system requires an investment of ~\$100M. The total service capability of such a system is 60K x 10 - 600K user-years. Then, from Figure 10, at a shared system user charge of \$50/month, a rate of return of 5% is possible at a market size of 480K user-years. (A = .8, G = .37). Note, that in this case the system is not required to be initially filled (A = 1.0) to generate at least a 5% rate of return. On the other hand, there is no way for such a system to generate a 15% return at a user charge of \$50/month.

Figures 7 and 10 may also be used to address the question of system capacity given market characteristics.

Example:

Suppose that at \$50/month shared system user charge 20,000 users may be attracted to the satellite system each year. Further, assume that at \$40/month, 30,000 users are attracted each year. Over a 10-year design life, what size system should be deployed?

To find initial scoping parameters, note that if I_c = 0 and no system saturation, then at $\dot{N}$ = 20K users/year, $\int \dot{N}dt$ = 1×10^6 user-years, and at $\dot{N}$ = 30K users/year, $\int \dot{N}dt$ = 1.5×10^6 user years. From Figure 10, a system capacity of 200,000 can provide 1×10^6 user-years at a required charge less than \$50/month (~\$46/month). Also from Figure 10, a system capacity of 300,000 users can provide 1.5×10^6 user-years at \$40/month. Thus, if the assumptions used to generate Figure 10 are correct, the postulated market can be served. To resolve the question of what size system is "best", further analysis is required.

Figures 7 and 10 were used to generate Figure 11, showing the required market growth rate as a function of user charge C_u. System size C is a parameter, and it was assumed that I_c = 0, i = 5% and t_o = 10 years. It is clear that C = 200,000 users is the best design choice.

Terrestrial System

Figure 12 showing system capacity as a function of shared system user charge was generated using equation (19). The assumptions were: m = .6; R_B = \$1M for C_B = 1000 users; and t_o = 10 years. Figure 12 is constructed as Figure 10 and it shows the per cell capacity of trunked and cellular systems. Figure 12 is scalable.

Comparison:

The systems parameters shown in Table 11 were selected for comparisons. It was assumed that each system was scalable via equation (11) over the area served. Equation (19) was then used to compute required capacity under the assumptions of G = .37, i = 5%, I_c = 0, A = .5 and t_o = 10 years.

Figure 13 then shows the required growth rate density (users/year/km^2) as a function of the shared system user charge. More than one order of magnitude separates the cellular and satellite systems. While available spectrum and technical requirements may limit the actual growth rates needed, the implication is that terrestrial and satellite systems may coexist based on user growth rate density. Areas producing high growth rate densities will be served by terrestrial systems, while areas producing low growth rate densities will be served by satellite systems.

CONCLUDING REMARKS

The concepts, equations and figures presented provide basic tools for analysis of both satellite and terrestrial land-mobile systems. There has been no attempt to be all inclusive in the cases covered. Order of magnitude analysis suggests roles for all systems considered based on the concept of user growth rate density.

Many variations of these analyses can and will be made as technical and cost data become available.

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TABLE I. - SYSTEM CAPACITY

Parameter	Cellular		Trunked		Satellite	
	Minimum density system	Maximum density system	Minimum density system	Maximum density system	Minimum density system (1 beam)	Maximum density system (100 beams)
Cell radius (km)	12.9	1.61	40.2	16.1	--------	---------
Cell area (km^2)	430.5	6.73	5083	813	7.5×10^6	7.5×10^4
Frequency band divisions	12	7	--------	------	--------	---------
Channels/cell	28	48	5	48	333	111
Capacity (erlangs) (P_B = 0.02)	20.2	38.4	1.66	38.4	330	99.5/beam
Density E/km^2	0.0469	5.706	3.3×10^{-4}	0.0472	4.4×10^{-5}	1.33×10^{-3}
Potential users/cell						
• Telephone						
at 0.03 E/user	673	1280	55	1280	11,000	3316
at 0.016 E/user	1262	2400	103	2400	20,625	6218
• Dispatch						
at 0.004 E/user	5050	9600	415	9600	82,500	24,875
• If no. of telephone at 0.03 equals no. of dispatch						
Telephone	594	1129	48	1129	9,705	2926
Dispatch	594	1129	48	1129	9,705	2926
Total	1188	2258	96	2258	19,410	5852
Density (users/km^2)	2.76	333.5	0.019	2.78	0.0026	0.078

TABLE II. - SHARED SYSTEM BASELINE PARAMETERS

	Satellite system	Trunked system	Cellular system
Baseline investment	$200 M	$1.5 M	$8 M
Capacity*	200,000	5,000	23,000
Area served (km^2)	9.4×10^6	8,000	10,000
*Assuming half are radio telephone users and half are dispatch users.			
($/user)	$1000	$300	$348
($/km)	$21	$187	$800

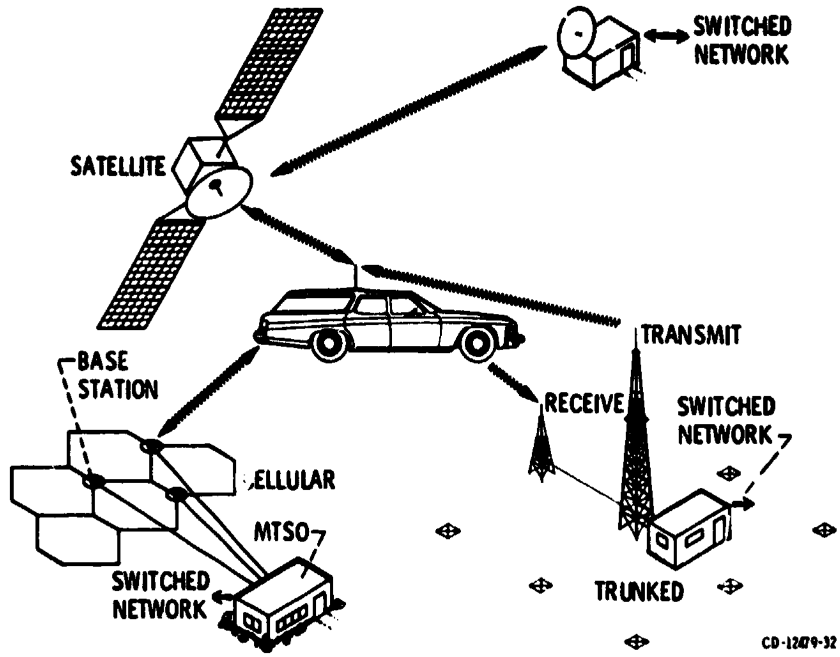

Figure 1.

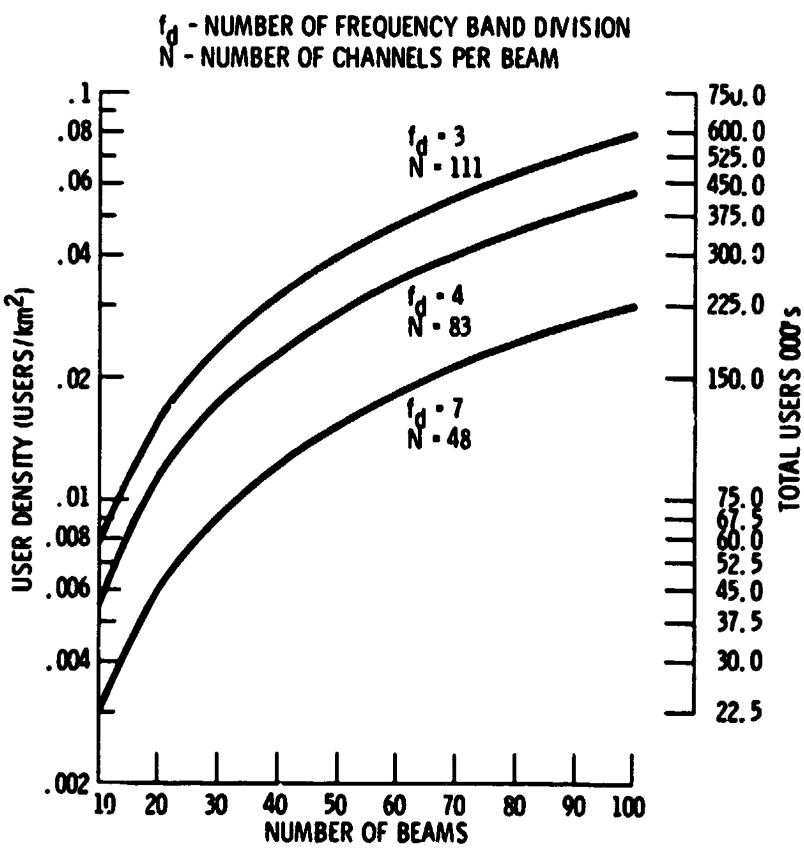

Figure 2. - Satellite systems capacity.

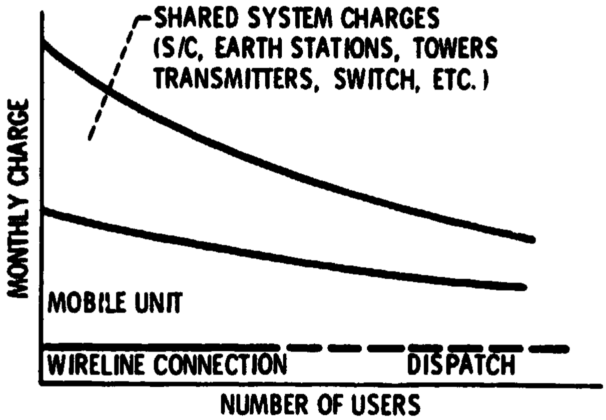

Figure 3. - User charge profile.

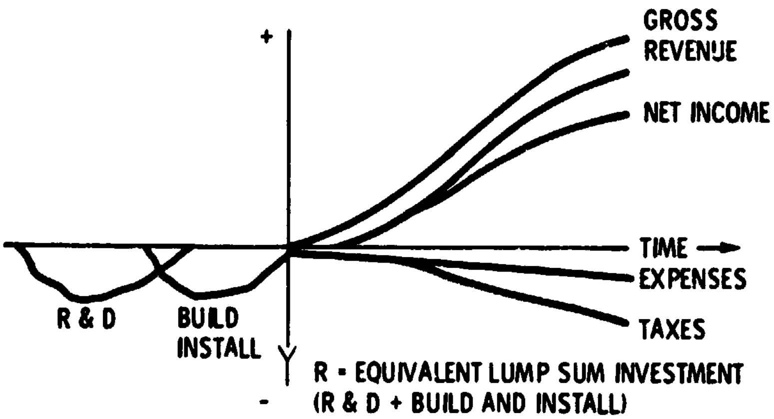

Figure 4. - Venture cash flow.

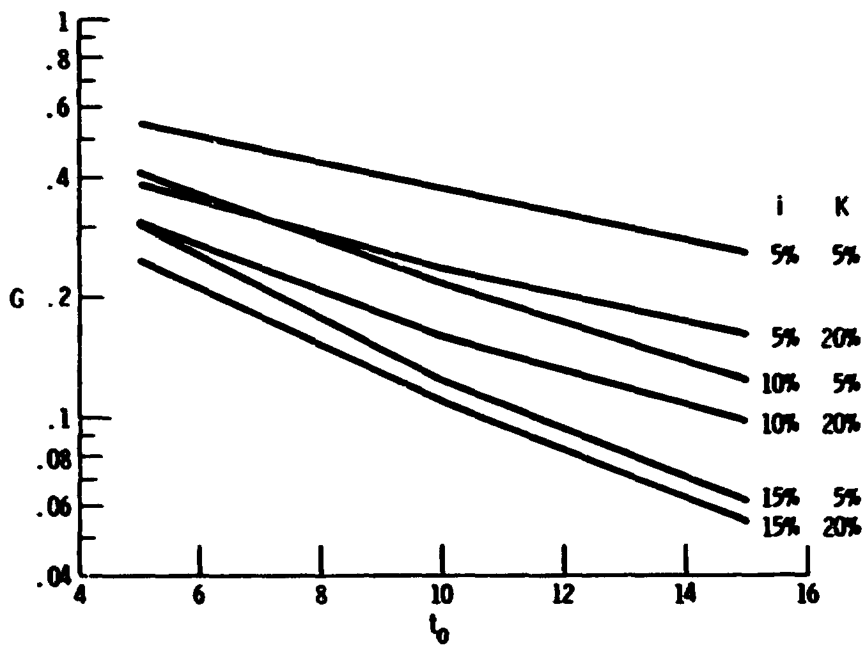

Figure 5. - Parameter G.

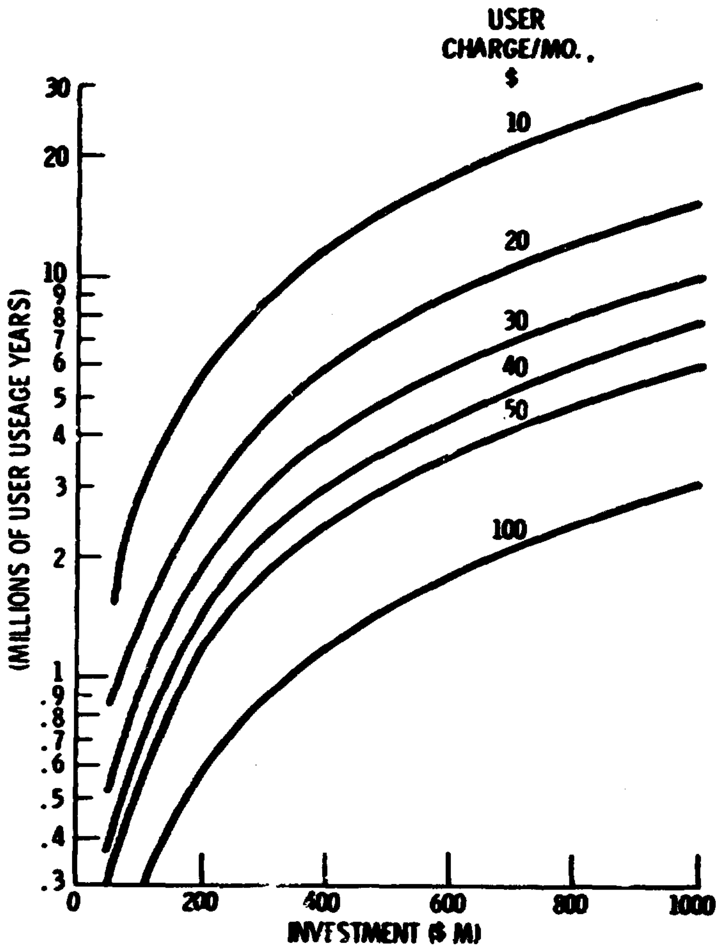

Figure 6. - System use (user years) vs. shared system investment.

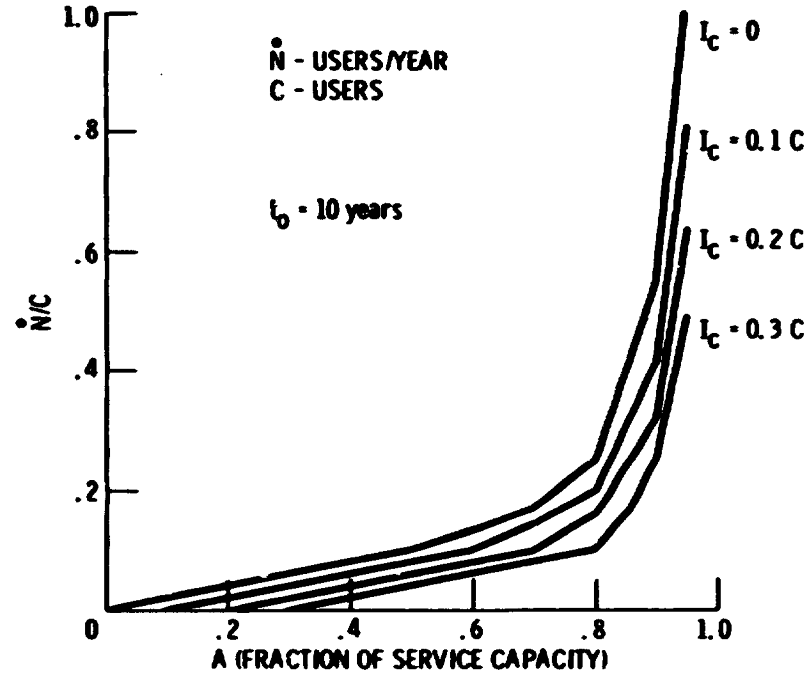

Figure 7. - Normalized rate of user increase vs. fraction of service capacity.

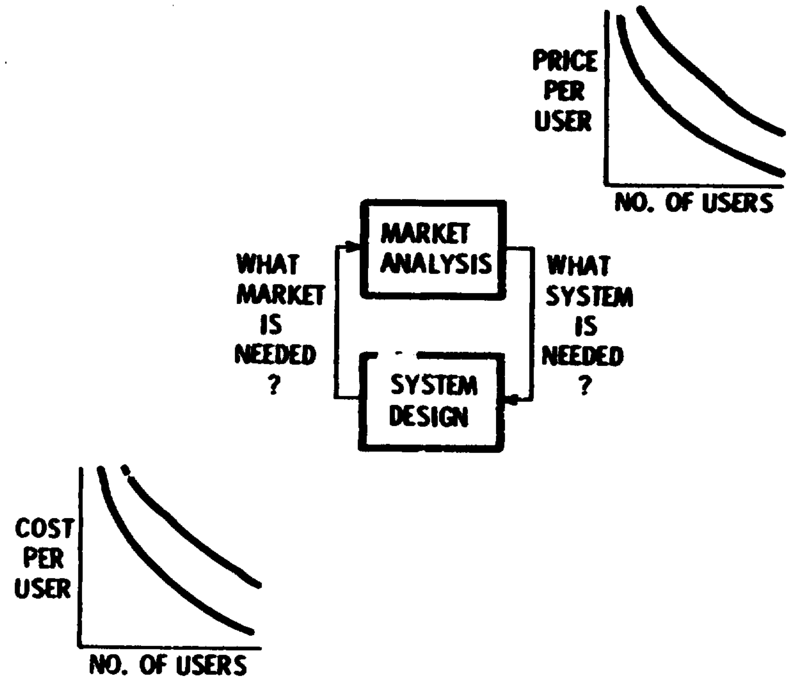

Figure 8. - Market - system design interaction.

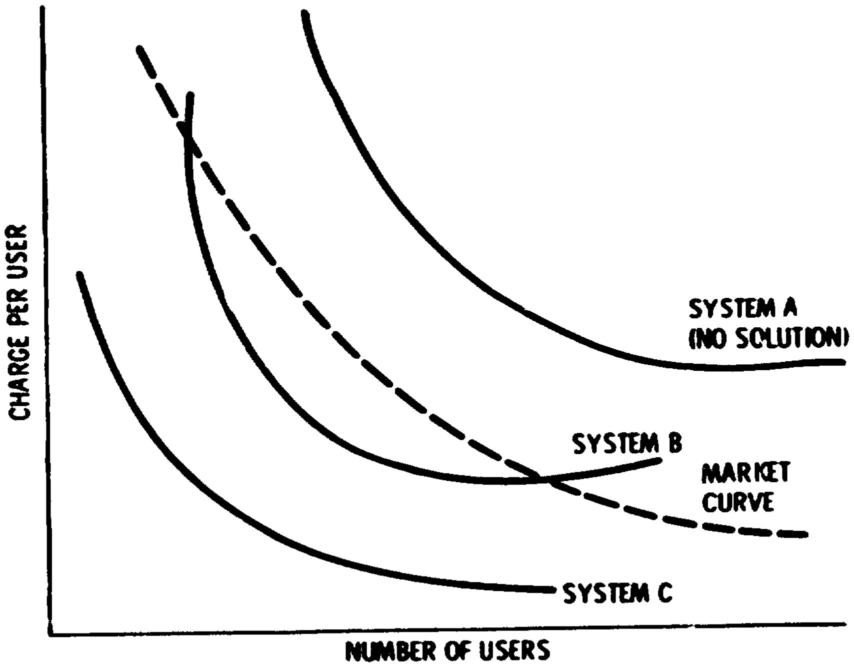

Figure 9. - System selection.

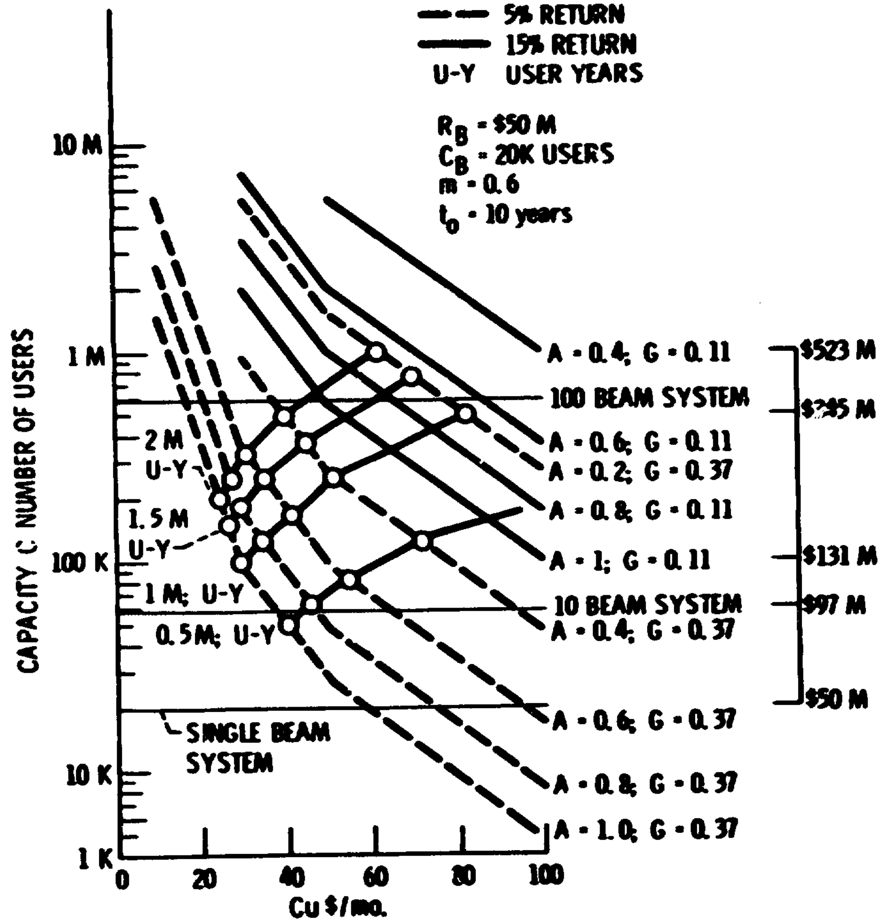

Figure 10. - System capacity vs. user charge.

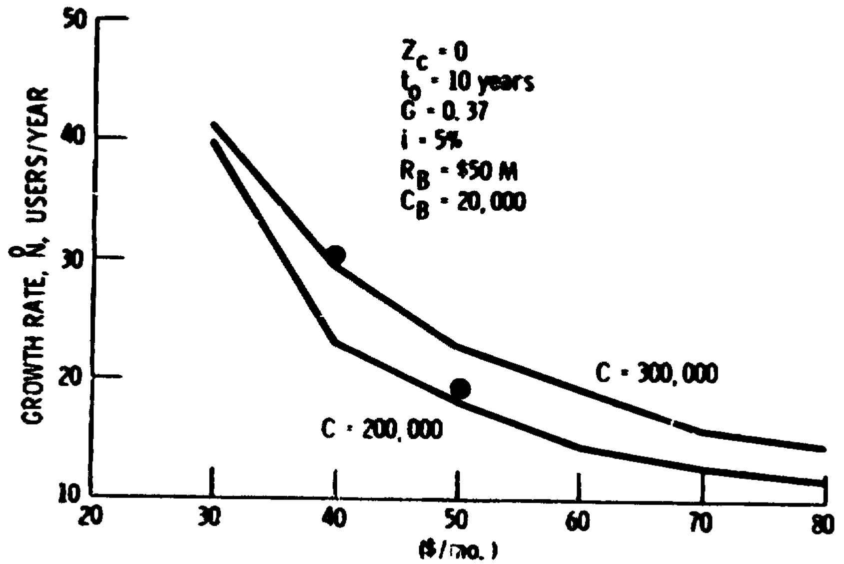

Figure 11. - Required growth.

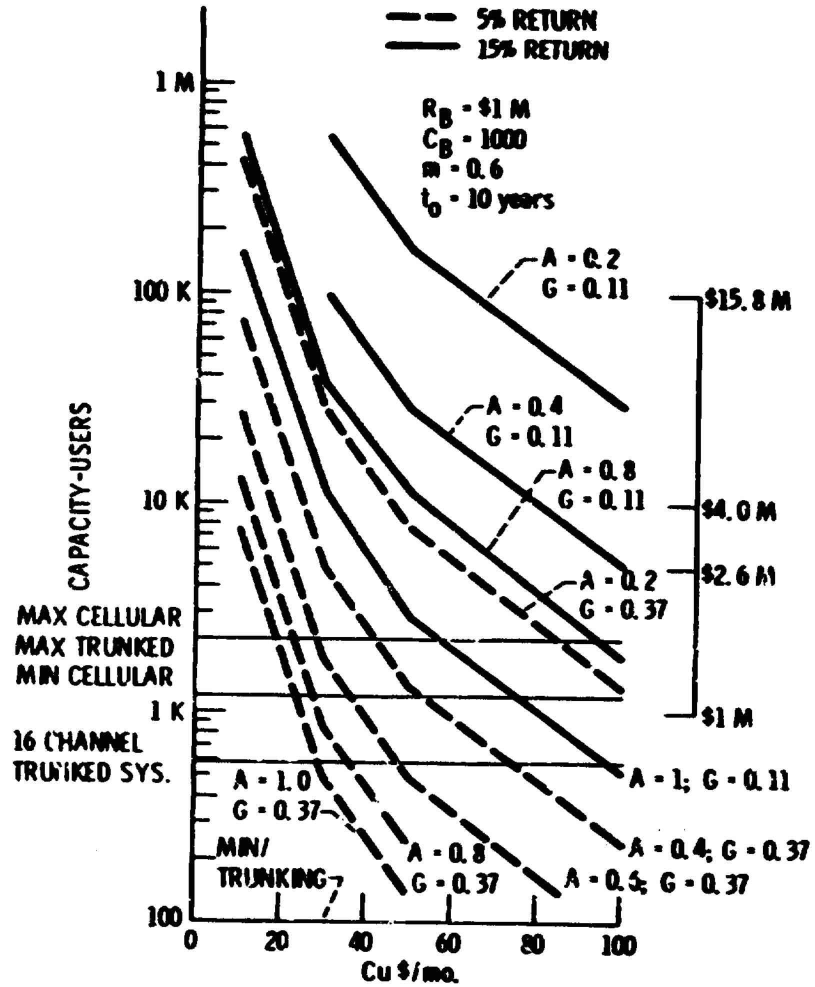

Figure 12. - System capacity vs. user charge.

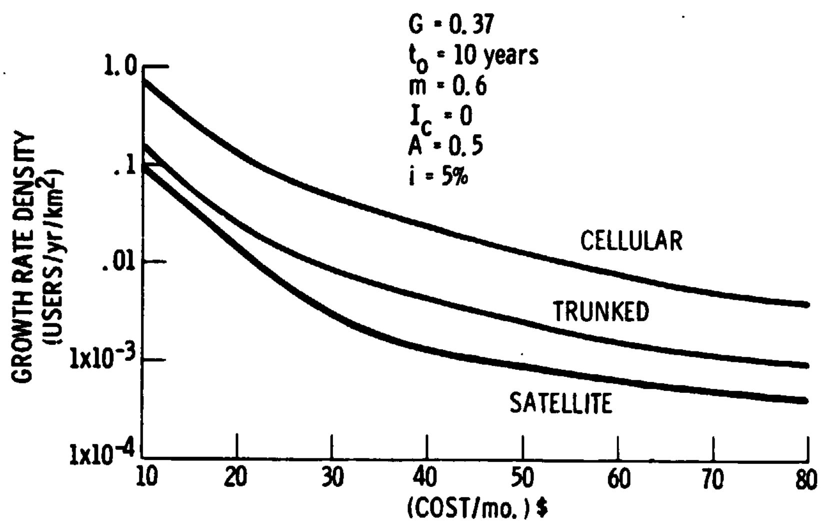

Figure 13. - Systems comparison.