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Using System Dynamics to Assess Economic Feasibility of Satellite-Augmented Cellular Networks

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Abstract

Success of future wireless data services will depend on the ability of mobile networks to support high bandwidth traffic. Deploying adequate cellular infrastructure might prove to be excessively expensive. Alternatively, instead of ensuring QoS through overcapacity, a cellular operator may buy satellite capacity to offload congestion in its terrestrial network. In this report, we use System Dynamics methodology to assess economic implications of such integrated hybrid networks. Computer experiments reveal that in the early stages of market development by augmenting its network with satellite capacity a cellular operator may improve its performance in terms of revenue, subscriber growth rates, profit and other business parameters. As more cellular capacity is deployed, the advantages of integrated systems disappear.

Keywords: mobile data services, economics of hybrid networks, system dynamics, satellite-augmented cellular network

1. Introduction

Because cellular networks capable of supporting future multimedia services will be extremely expensive (Zander 2001, Dutta and Hsu 2001), deployment of hybrid radio infrastructure has been proposed as an alternative to the massive cellular capacity buildup (Bria, Gessler, Queseth, Stridh, Unbehaun, Wu, Zander and Flament 2001). Some concept designs of hybrid systems advocate slow universal cellular coverage overlaid by high bandwidth "hot-spots" in the proximity of strategically-placed high-powered radio transmitters (Frenkiel, Badrinath, Borras and Yates 2000; Noble 2000; Zander 2001). Other designs envision terrestrial cellular systems, especially in hilly and mountainous areas, being complemented with satellite networks (Ayyagari and Ephremides 1998) and unmanned long-endurance airborne platforms (Mondin, Dovis and Mulassano 2001). Preliminary research also suggests that when compared to homogeneous networks hybrid networks may provide better quality of service (Ayyagari and Ephremides 1998, Jain and Varshney 2002) and greater reach (Hudson 2000).

It has not yet been made clear, however, if such integrated systems will make mobile multimedia service provisioning more economically attractive for mobile operators. In this paper, we review economics of a satellite- cellular hybrid system. For our analysis, we use System Dynamics methodology, which has been applied to telecommunications industry more than once. For example, Lyneis (1994) developed a model for the analysis of strategic and tactical decisions within a telecom firm concentrating on labor requirements. Recently, Pettersson and Rabelo (2002) applied System Dynamics to study the feasibility of the transition to 2.5G and 3G radio technologies. Experiments with our model suggest that satellite-augmentation might be an attractive option for cellular operators in the early stages of service deployment – when subscriber base is still small and the cellular network has few access points. As more cellular capacity is deployed, the advantages of integrated systems disappear.

Section 2 describes the general organization of the model and explains individual sectors of the model. We present experiments in Section 3. Section 4 concludes.

2. Model

Three types of players covered in this analysis are: (i) cellular operators that make decisions with respect to cellular network capacity and the price of the mobile service; (ii) satellite operators that sell high bandwidth transmission to cellular operators; (iii) end-users that set market demand based on data service price and quality.

2.1 Overall structure of the model

The model consists of seven sectors, as can be seen in Figure 1. The sectors are:

1. Cellular infrastructure
2. Mobile service pricing
3. Competition
4. Satellite network
5. Financials of the cellular operator
6. Subscriptions
7. Infrastructure cost-based pricing input

Arrows in the diagram correspond to the functional connections between the sectors.

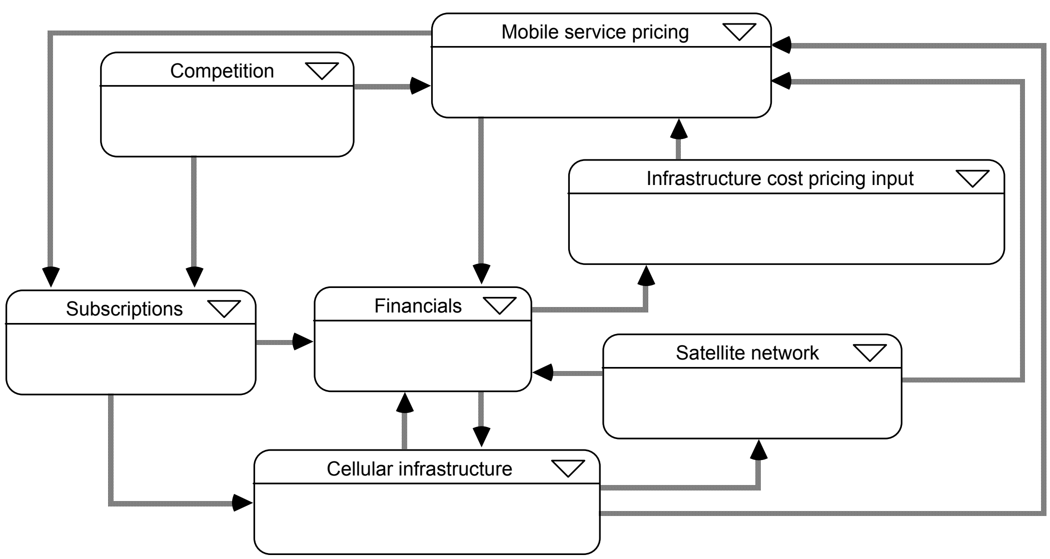


Figure 1: Top view of the model

2.2 Individual sectors

3.2.2 Cellular infrastructure

Figure 2 shows the cellular infrastructure sector. The number of installed base stations and the capacity of each individual base station determine the traffic capacity of the cellular network (Zander 2001). Cellular network utilization is defined as the ratio of the current network traffic to the overall capacity of the system. Traffic is a linear function of the subscriber base adjusted by the factor we call “subscribers to users ratio.” The adjustment factor is necessary because only a fraction of all subscribers uses the system at each moment (Dutta and Hsu 2001). Basic network traffic theory suggests a non-linear relationship between network utilization and average blocking probability. Blocking probability is defined “as the average fraction of new call requests that cannot be served” (Ayyagari and Ephremides 1998: 192). Among many quality indicators used by the telecommunications industry (Zander 2001), blocking probability is one of the most popular measures (Pecar and Garbin 2000: 412; Ayyagari and Ephremides 1998). Average blocking probability is implemented as a lookup table. Typically, we would also need to take handover requests into consideration since they also contribute to traffic. However, in this model we choose to omit handoffs. Further extensions of the model will add this detail. Blocking probability is negatively related to the cellular transmission service quality (Viterbo and Chiasserini 2001), which is defined as 1-P, where P is the call blocking probability.

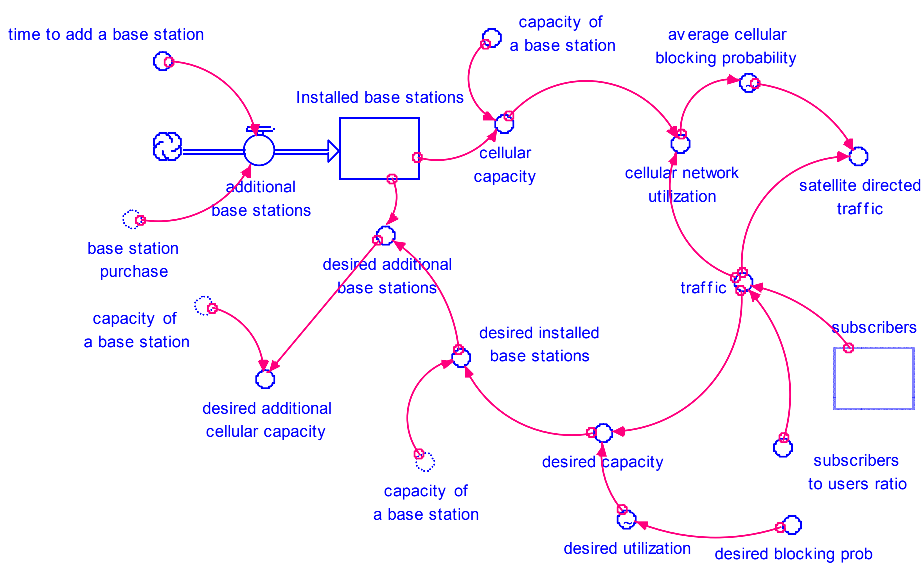


Figure 2: Cellular infrastructure of a mobile operator

Good practice in the telecom industry is to have a grade of service (in terms of blocking probability) no more than 5 percent and preferably in the 1 to 2 percent interval (Pecar and Garbin 2000: 426). For given traffic this requirement translates into a certain desired network capacity that can be achieved with a certain number of base stations. The difference between the number of desired base stations and the stock of installed base stations is the number of desired additional base stations. As explained in the Financials sector, purchase of new base stations is limited by the budget constraint. With some delay, new access points are added to the stock of base stations.

3.2.3 Satellite sector

Satellites may perform two functions that are advantageous to the cellular network operator. Firstly, satellites can provide "out-of-area" coverage for mobile users and, secondly, if narrow beam antennas and switchable spot beams are utilized, satellites may augment localized overloaded cellular network (Ayyagari and Ephremides 1998). The latter situation is addressed in this report and is schematically shown in Figure 3. Previous work (for examples, see, (Hu and Rappaport 1995; Ayyagari and Ephremides 1998)) suggests that using satellites to offload congestion might result in better blocking performance of the integrated system without the need for overcapacity.

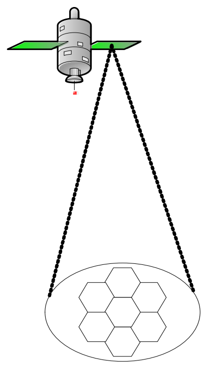


Figure 3: Satellite-augmented cellular network

Figure 4 is a rendition of the satellite network sector. We assume that a satellite operator has a fixed stock of satellites. For instance, Teledesic – one of the satellite operators that may potentially participate in a hybrid network – has 288 LEO satellites each capable of handling 155.52 Mbps to and from the ground (Varshney and Vetter June 2000). Assuming that the satellite operator will use some capacity for its own native traffic, the space system will be operating at a certain utilization level. As for any communication network, utilization determines the blocking probability for all new call requests.

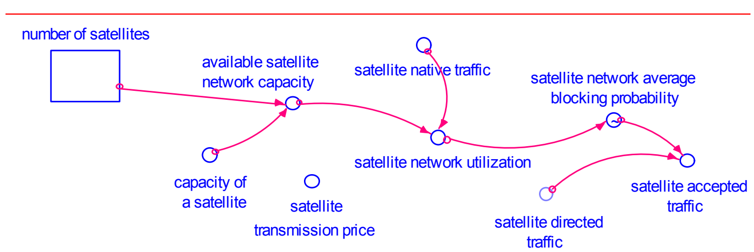


Figure 4: Satellite network provides additional capacity

We assume that the cellular operator follows a cell-first traffic control algorithm (Hu and Rappaport 1995; Ayyagari and Ephremides 1998). In the cell-first procedure, call requests are directed to the cellular system and, if it is not available, to the satellite network. Assuming, as in (Ayyagari and Ephremides 1998: 192), that there is always a visible satellite, the probability that the redirected call is admitted by the satellite operator depends on the current blocking probability of the satellite network.

High expectations for the business applications of space (Dobbs 2001), have not yet materialized for good practical reasons. In the case of satellite communications, relatively high prices (Hudson 2000: 286) have led to its very modest economic success (Varshney and Vetter June 2000). In this model, we assume fixed price for satellite transmission, which is greater than the base cellular transmission price. However, as our analysis suggests, even though the price of space transmission is high, the symbiotic relationship with the space operator may be beneficial to the terrestrial operator.

3.2.6 Financials

The Financials sector (Figure 5) keeps track of the cellular operator's revenue and expenditure streams. For the seed capital, the operator takes a loan, which is then used to purchase initial stock of new base stations capable of handling broadband data traffic. Alternatively, the same seed money can be spent to upgrade existing base stations. The initial number of access points is limited by the seed capital and the cost of each base station, which includes hardware cost and some additional costs, such as, planning, deployment, cabling, housing, real estate, construction cost, etc. (Zander 2001). The debt is then paid in monthly installments, which are inversely related to the length of the loan. Average monthly infrastructure cost is the average of loan payments and the total network maintenance cost. Maintenance cost includes such expense groups as facilities, property/tax, remote diagnostics, billing, repair, etc. Revenue is channeled into available capital. The amount of available capital sets the limit on further investments. Future extensions of this model may take the spectrum license cost into account (Zander and Kim 2001).

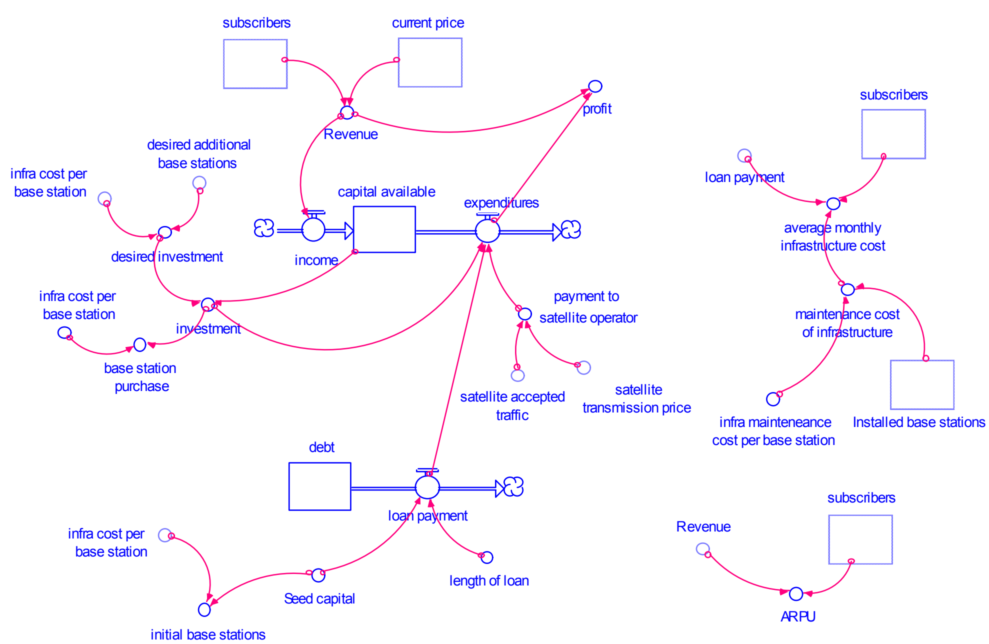


Figure 5: Financials sector that includes revenue, expenditures and loan obligations of the mobile operator

3.2.7 Subscriptions

The subscriptions sector, Figure 6, models service adoption. It is based on a well-known and widely-used quality-differentiation microeconomic framework (see, for example, Economides 1999). Quality differentiation models recognize that consumer preferences are non-homogeneous (Mitchell 1978), and therefore consumers value the same data service differently. For instance, if the service will deliver movies on-demand, then some end-users will be willing to pay more than at a movie theater for the ability to watch a movie on the go, but others would never spend a dime on it. Heterogeneous preferences are approximated by assuming that *willingness to pay*, u ,is distributed randomly between zero and one according to some statistical density function $f(u)$ (Economides 1999; Mitchell 1978). Although, generally, valuations for different services may have distinct distribution functions, many of which, of course, are still unknown, to keep things simple, we follow Economides and Lehr (1994) and review a special case when willingness to pay is distributed uniformly, that is, $f(u) = 1$.

Assuming a linear relationship between benefit and quality of service (Economides 1999), the consumer's utility derived from service of quality q_s is uq_s. Then at price p_s, a customer enjoys surplus $uq_s - p_s$. Only clients for whom surplus is positive, that is, $uq_s - p_s \geq 0$, subscribe to the service. The intensity of preference for quality for such customers, measured in terms of willingness to pay, u, is greater than some threshold value, that is, $u \geq \overline{u} = p_s / q_s$. From the basic probability theory it then follows that the proportion of end-users that buy the service is

$$\int_{\overline{u}}^{1} f(u)du = \int_{\overline{u}}^{1} 1du = 1 - \overline{u} = 1 - p_s / q_s$$

Denoting the total market size – which is simply the sum of all the potential and current subscribers – as k, market demand for data service is

$$D(p_s, q_s) = k(1 - p_s / q_s)$$

Such a linear approximation of demand, though simple, explicates two empirical facts: (i) the law of demand, that is, higher prices suppress demand; and (ii) higher levels of mobile service quality stimulate consumption levels (Bolton 1998). The formulation has proven to be effective for the analysis of telecom and has been popularized, among others, by such prolific and influential economists as Mitchell (see, his early article, 1978) and Tirole and Laffont (see, for example, their recent monograph, (2000)). In this model, we assume that the market demand is determined by the highest available quality to price ratio, which measures service attractiveness.

Consumer decision delay models the time it takes to change the end-user's attitudes toward a new service. There is a number of reasons for the delay. Firstly, tastes and preferences take some time to develop. Secondly, current cellular service in the United States is characterized by the existence of long-term contracts – customers must commit for a specified period of time, usually one or two years for the retail market, to the provider. Therefore, even if unhappy with the service, a subscriber may not be able to immediately abandon the contract.

We assume that the mobile operator captures a fraction of the total market demand proportional to the attractiveness of its service as compared to the service offered by the competitor. Therefore, lower price has a positive effect on the market share. The same effect is achieved by improving quality of service.

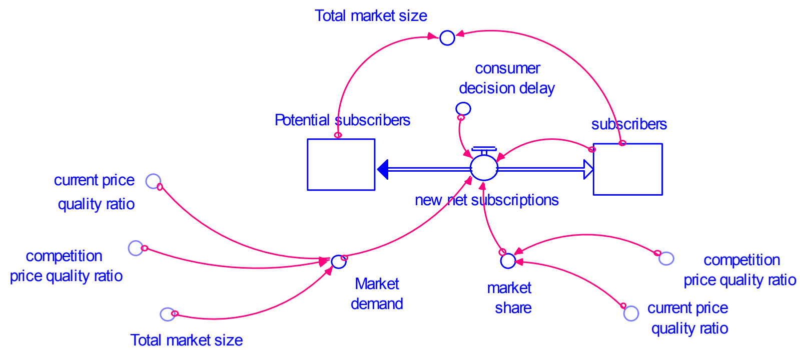


Figure 6: Subscription sector

3.2.4 Competition

According to a recent report by the Federal Communications Commission (2002: 5), almost all of the United States population lives in areas with at least three mobile operators, each of them competing for the same pool of customers. The situation is similar in the other market economies of the world. Competitive force is important to the dynamics of the mobile industry (Rosenbush, Crockett, Haddad and Ewing 2002) and it typically drives prices down (Xavier 1997). For example, in Hong Kong, which is one of the most competitive wireless markets, revenue per minute fell from US$.37 to US$.15 between 1998 and 2000 due to the heavy competition (Leibowitz 2000: 80). Besides price, operators also compete on quality (Leibowitz 2000). Quality does not necessarily need to be the best to attract a customer. As the success of iMode by NTT DoCoMo in Japan shows when priced correctly even low bandwidth service (iMode is only 9.6 Kbps) can dominate the market. DoCoMo has been successful because fixed line service in Japan, which is faster, has been historically overpriced (Leibowitz 2000: 79). We capture service attractiveness to the end-user through the price-to quality ratio. For this implementation, we choose fixed competitive price and quality that serve as references for the cellular operator. Figure 7 shows the competition sector.

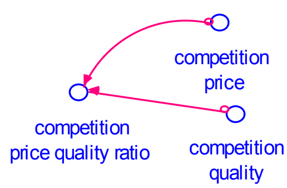


Figure 7: Competition is represented through price and quality

3.2.5 Infrastructure cost pricing input

Mobile operators are under pressure to recoup capital investments, and therefore, typically, the return on investment target is prominent in price setting (Xavier 1997). When the Average Revenue per User (ARPU) is too far off from the average monthly infrastructure cost, the pressure to increase the base price will mount. The greater the discrepancy between the network cost and ARPU is the stronger the pressure to adjust price is. The sector that captures the cost input into pricing is depicted in Figure 8.

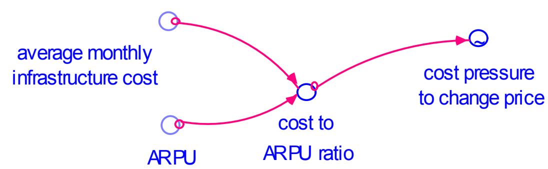


Figure 8: Pricing input due to the cost of the network

3.2.1 Mobile service pricing

The telecommunication industry has relied on a variety of pricing schemes and pricing principles (Mitchell and Vogelsang 1991, Xavier 1997, Laffont and Tirole 2000). Extensive literature on the subject produced such well-known insights as, for example, when a two-part tariff is used, to keep the number of subscribers constant, as the per call charge goes up, the mobile operator has to lower the fixed fee (Mitchell 1978). We also know that a two-part tariff is equivalent to the quantity discount pricing: the more someone buys the cheaper the average price becomes (Tirole 1993).

The cellular market produced a girth of new charging schemes: rates changing with the time of the day (peak and off-peak minutes), rates based on the originating location of the call (roaming), geographic price discrimination (home, regional, and national service plans), discrimination based on the number of subscribers on a contract (family plans), and so forth. Mobile providers are continuously changing and experimenting with their service packages.

At this stage, it is hard to predict which pricing scheme will dominate the market for mobile data services. In fact, there may be an array of schemes and tariffs used. For movies on-demand consumers might be charged per movie. A currently observed pricing per instant message, or pricing per Mbits of traffic (Leibowitz 2000: 78) might also survive. Some new schemes might be influenced by the experiences with the Internet (Gupta, Stahl and Whinston 1995). For example, the expectation of future high volume multimedia traffic may result in adoption of novel types of pricing schemes designed to mitigate network congestion and improve network performance (Viterbo and Chiasserini 2001; Heikkinen 2002). Therefore, this model's subscription fee should be interpreted as a proxy for future, possibly quite sophisticated, pricing mechanisms. Although this is a simplification, it serves our purpose well in illuminating general price levels. The price dynamics sector is shown in Figure 9. Price adjusts in response to the competitiveness of the price-to-quality ratio and the need to recoup the cost of infrastructure. Saeed (2003) recently applied a similar pricing mechanism in the mitigation banking context. General description of the mechanism can be found in (Sterman 2000).

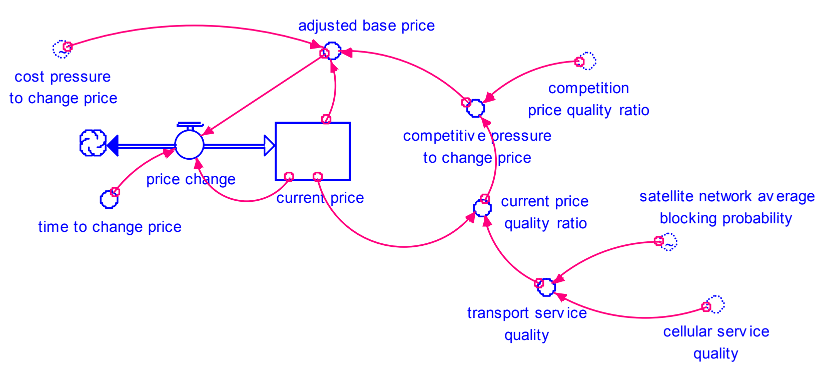


Figure 9: Mobile service sector

3. Results of computer experiments

The purpose of this report is to assess economic implications of augmenting basic cellular infrastructure with the capacity of a satellite operator. To achieve this goal, we build a model that allows simulating a cellular operator that either provides services alone or provides them together with a satellite operator. The model was implemented in *iThink Analyst* that allows sector selection.

Simulations suggest that adding satellite capacity:

(i) improves the revenue stream for the cellular operator, which leads to better ARPU figures;
(ii) allows the cellular capacity to build up over a longer period without sacrificing quality;
(iii) may induce higher service prices due to better service quality;
(iv) improves service quality and encourages new subscriptions;
(v) improves profit of the cellular operator but only in the initial stages when subscribers are few and the cellular network is still in its budding stage.

3.1 Comparative business performance

Having a satellite network as a back up for a cellular system improves overall transmission quality (Ayyagari and Ephremides 1998, Jain and Varshney 2002). Better quality affords premium service price. Figure 10 shows that early in the deployment, the satellite-augmented network will be able to command higher price (curve 2) than the cellular network (curve 1). Supported by the robust subscriber growth, Figure 11, revenue stream is also better in the hybrid network. Figure 12 depicts the time series for the revenue stream. In all graphs in this section, curves labeled “1” are for the cellular-only case and curves “2” are for the satellite-augmented system. Revenue growth and subscriber growth together yield a very attractive ARPU numbers for the satellite-augmented network (Figure 13).

In the initial stage, the high volume of traffic redirected to the satellites does not leave much capital for infrastructure investment. Therefore, demand growth outpaces capacity growth leading to a sharp decline in the cellular transmission quality, shown as curve 2 in Figure 14. Notice that eventually, the cellular operator builds up the network to the level it would have reached without the satellite partnership, that is curves 1 and 2 in Figure 14 converge. We should note that even though the capacity of the cellular network in the hybrid case lags behind, the subscriber receives data service of good quality due to the satellite support.

Having a smaller cellular network, and therefore lower maintenance costs, in the hybrid case, lowers the cost-related pressure on prices (Figure 15). Therefore, the higher prices we have seen in Figure 10 are exclusively due to the better quality of the final product.

Figure 16 displays the profit time series for the cellular operator. Clearly, the operator earns greater profit in the initial stages if it participates in the hybrid network. However, lost revenue due to redirected traffic and payments to the satellite operator will eventually lower profits below the levels of an independent cellular operator.

Figure 17 captures the causal structure of the hybrid system. When the satellite operator is not participating in the transmission, then the *satellite directed traffic* and *payment to satellite operator* are zeros.

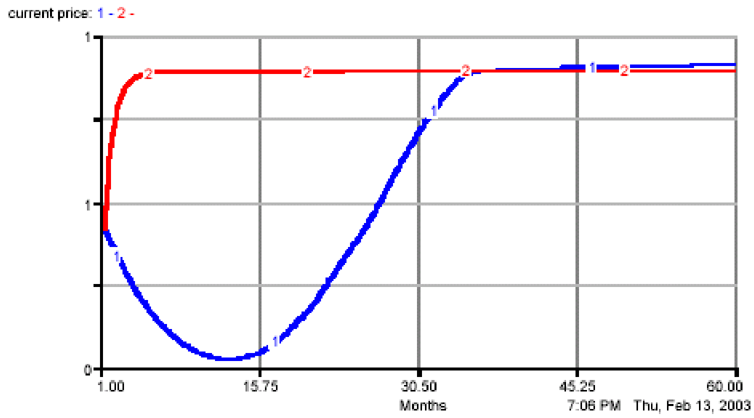


Figure 10: Mobile service price in the cellular (1) and hybrid (2) networks

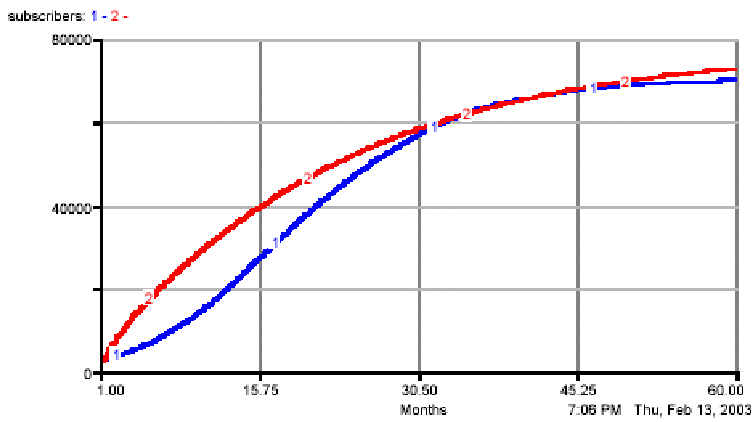


Figure 11: Number of subscribers in cellular (1) and hybrid (2) networks

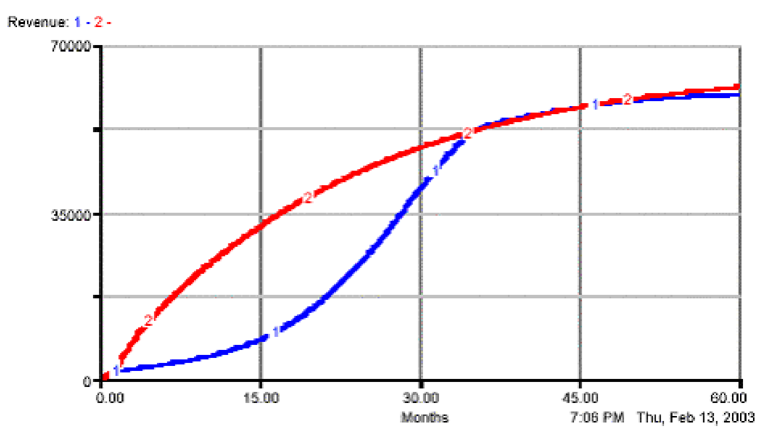


Figure 12: Revenue for the cellular (1) and hybrid (2) networks

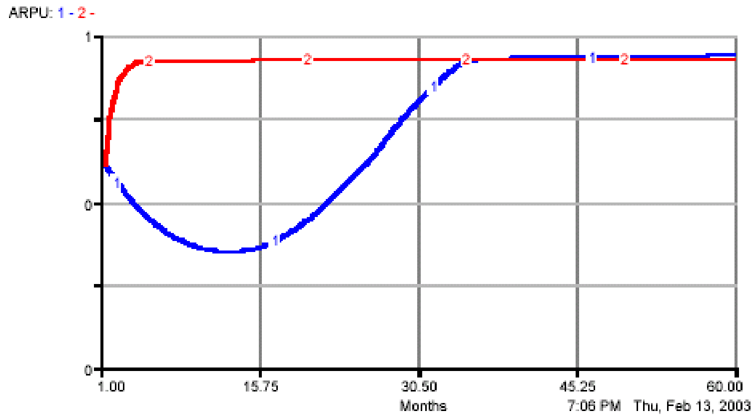


Figure 13: Average revenue per user for the cellular (1) and hybrid (2) networks

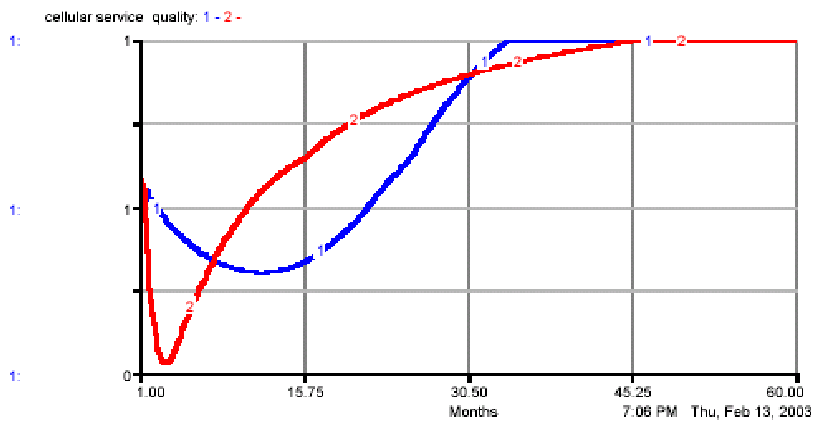


Figure 14: Quality of the cellular network without (1) and with (2) satellite-augmentation

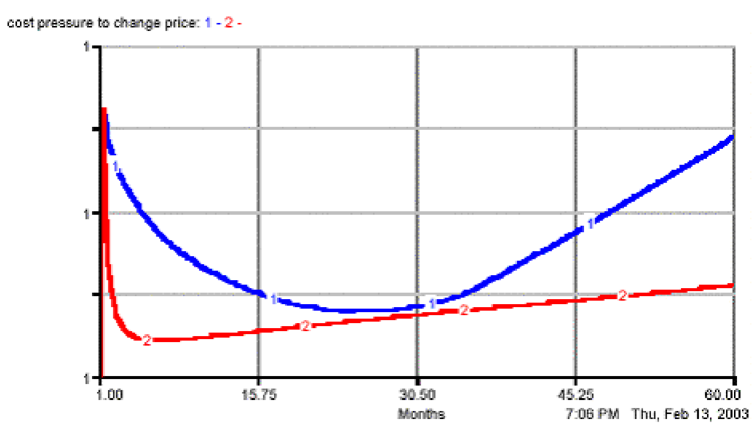


Figure 15: Cost pressure to change price in cellular (1) and hybrid (2) networks

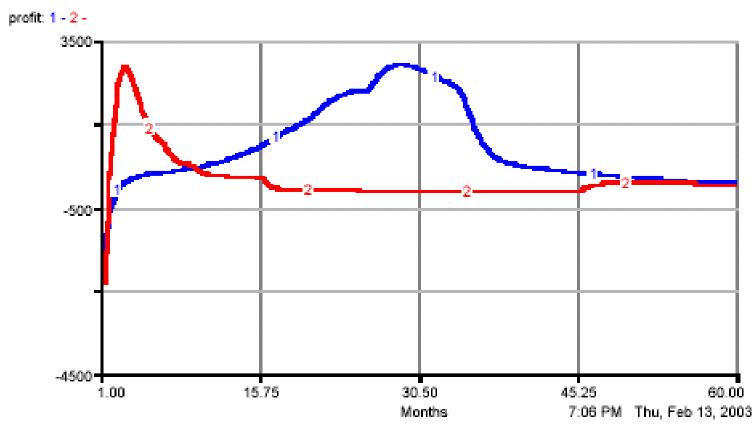


Figure 16: Profit trajectories for cellular (1) and hybrid (2) networks

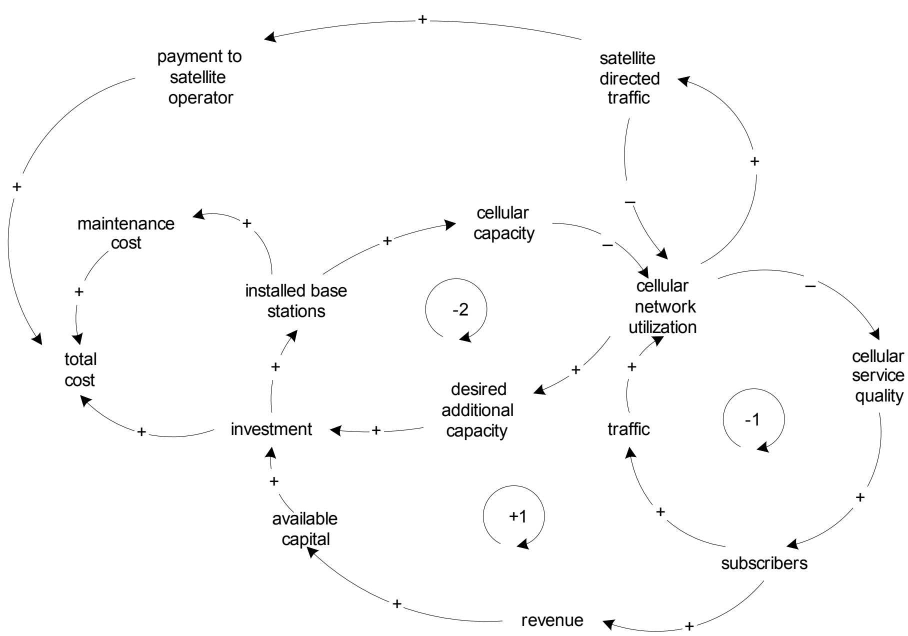
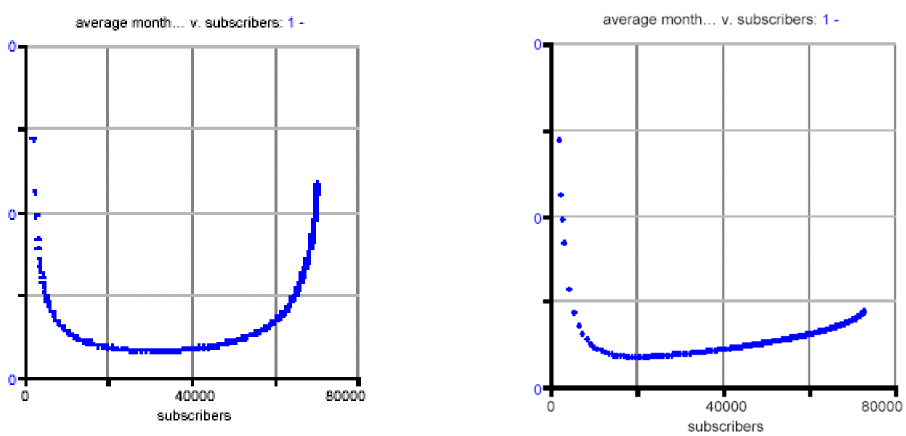


Figure 17: Causal structure of the hybrid system

3.2 Tracking economic fundamentals

Statistical analysis of the cost data for cellular operators by McKenzie and Small (Mckenzie and Small 1998) showed that operators exhibit either constant or negative economies of scale. This is expected from the engineering-based cost structure analysis of cellular networks (Zander 2001). Since we attempted technical accuracy in this model, it is not surprising that simulations generated the same type of economies as found by McKenzie and Small. Figure 18a displays an average monthly network cost in relationship to the subscriber base. Even though initially operators experience positive economies of scale – that is the average cost drops as the operator grows – constant or even negative economies eventually manifest themselves. The absence of positive economies of scale is the primary reason that cellular networks may be too costly to support multimedia traffic (Zander 2001). Figure 18b demonstrates that supplementing cellular transmission with satellite relay, that is, forming a hybrid network, mitigates the nonlinear effect in the cost function (Zander 2001) and results in milder diseconomies of scale for the cellular operator. Both graphs are plotted for the same subscriber and cost ranges.



a) cellular network

b) hybrid network

Figure 18: Economies of scale

4. Conclusion

This paper reviewed the economics of satellite-augmented cellular networks. By building a system dynamics model and conducting computer experiments, we learned that, if a cellular operator participates in a hybrid network, its revenue, subscriber growth, and profits improve especially in the early stages of the market development. As more cellular capacity is deployed, the advantages of an integrated system disappear.

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