THE REAL OPTIONS TO TECHNOLOGY MANAGEMENT: STRATEGIC OPTIONS FOR THE *3G* WIRELESS NETWORK ARCHITECTURE AND TECHNOLOGIES

by

Hak Ju Kim

B.S. in College of Business Administration, Korea University, 1988

M.B.A. in College of Business Administration, Korea University, 1990

M.S. in School of Engineering, University of Colorado at Boulder, 1999

Submitted to the Graduate Faculty of

The School of Information Sciences in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2004

UNIVERSITY OF PITTSBURGH

SCHOOL OF INFORMATION SCIENCES

This dissertation was presented

by

Hak Ju Kim

It was defended on

April 2004

and approved by

Richard A. Thompson, PhD, Professor

David Tipper, PhD, Professor

Benoit Morel, PhD, Professor

Ravindranath Madhavan, PhD, Professor

Dissertation Director: Martin B. H. Weiss, PhD, Professor

THE REAL OPTIONS TO TECHNOLOGY MANAGEMENT: STRATEGIC OPTIONS FOR THE *3G* WIRELESS NETWORK ARCHITECTURE AND TECHNOLOGIES

Hak Ju Kim, PhD

University of Pittsburgh, 2004

The fundamental importance of *Real Options* has been recognized in academics and in actual practice as a strategic tool to manage uncertainty. However, the use of *Real Options* to reframe one's approach for solving problems or to build additional flexibility into systems has been neglected. Although the notion of *Real Options* has recently received some attention in network industry, its potential value still remains uncertain and its emphasis on flexibility is only loosely related to the goal of creating value in existing networks. So, we need better explanatory models for the value of flexibility in networks.

The traditional real options approaches (ROA) have usually focused on the issues concerning decisions for business investments, such as mining, oil, medicine R&D, and other investment activities. However, in this study, ROA directly approaches technology itself to assess its value, especially wireless network technologies (e.g., AMPS, *GSM*, *CDMA*, *WCDMA*, *cdma2000*, etc.). This study proposes a theory to show how technology options affect on the value of a network (i.e., wireless network) using ROA. We also develop a model to show explicitly the value of technological flexibility (i.e., technology choice) on a firm's technology strategy in the wireless industry.

At present, there are many alternative wireless network technologies, such as *TDMA*, *GSM*, GPRS, EDGE, *WCDMA*, and *cdma2000* in generations. These wireless technology choices require close examination when making the strategic decisions involving network evolution. The evolutionary paths to *3G* from the principal *2G* technologies, *GSM* and *CDMA*, in wireless networks, are quite distinct. One path calls for 'Code Division Multiple Access (*CDMA*)-based network migration', which requires extensive infrastructure replacement (*architectural*

innovation), while the other path, 'Global Systems for Mobile Communications (*GSM*)-based network migration', requires the existing network to be upgraded (*modular innovation*).

The goal of this study is to develop a theoretical framework for wireless network operators to support their strategic decisions when considering technology choices as they move to the next generation wireless network (i.e., *3G*) architecture. This study begins by tracing the evolution of technologies in wireless networks to place them in the proper context, continues by developing the real options approach as an assessment tool when deciding among competing various network technologies. Finally, this approach is simulated through a case study in the formulation of strategy on wireless network architecture and technologies in the United States.

Consequently, this study will help wireless network service providers make strategic decisions when upgrading or migrating towards the next generation network architecture, by showing which network migration path leads to the most optimum results. Through this study, network designers can begin to think in terms of the available network design options and to maximize overall gain in network design. Since the areas of the next generation wireless network architecture and technologies remain the subject of debate with no substantial implementation taking place, there is much work to do. With further research, this study can be expanded and further developed.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

1.1 BACKGROUND

1.1.1 Industry and Market

Currently, the network industry is faced with high uncertainty with respect to its markets and technologies. Examples are the increasing demand for multimedia services and the highly competitive environment. So, to meet customers' demands and to survive the market pressures, network service providers (NSP's) require strategic management skills to successfully upgrade or replace their networks. The surviving network service providers, such as ISPs, CLECs, ILECs, or even recent *3G* wireless service providers, are facing an environment in which experimentation is needed to determine the most viable business, cost, or service models.

As the global wireless industry moves toward *3G* standards, the three major *2G* standards (GSM, TDMA, and CDMA) coexisting now in the world will most likely lead to two competing *3G* standards (cdma2000 and WCDMA). The *CDMA* technology standard will evolve to *cdma2000*, and the *GSM* technology standard will evolve to *WCDMA*.

Since the US wireless technology policy supports the coexistence of multiple standards to encourage competition, the US wireless industry is constantly evolving and it has become more competitive since the formation of a number of large providers such as Cingular-AT&T Wireless, T-Mobile, Verizon Wireless, Sprint PCS, and Nextel. These companies are presently competing in many of the same markets, driving consumer prices down. In addition, current US spectrum licensing policy allows service providers to choose whatever standard they deem appropriate, opening the door for the *GSM* standard to be used in the US market. On the other hand, the European wireless technology policy requires a single standard (GSM) that all service providers must adopt.

1.1.2 Services and Technologies

With the emerging trend of mass customization and personalization (Pine 1993; Anderson 1996; Pine 2000), providing customized and rapid services has recently been identified as an important competitive advantage in the business world, including the network industry. Service development is no longer about creating the service itself, but also about creating a platform on which to provide it (Sanchez 1995). The notion of service architecture design is a key concept in service development, and it is no longer just a technical issue (Anderson 1996).

The increasing demands for high-quality multimedia services have challenged the wireless industry to rapidly develop wireless network architecture and technologies (Garg 2001). These demands have led wireless service providers to struggle with the current network migration dilemma, i.e., how to best deliver high-quality multimedia services. These services are the foundation of multimedia and interactive information systems that service providers expect to contribute most to future profits. To that end, equipment providers have been developing a series of technologies, referred to as "*Third Generation*", or *3G* (Carsello 1997; Dahlman 1998; Dravida 1998; Prasad 1998; Garg 2001; Dalal 2002), to support these services.

Creating appropriate network architectures to support new services is now central to NSP's strategies. One of emerging methods is to create more flexible network architecture (Carsello 1997; Dahlman 1998; Dravida 1998; Prasad 1998; Garg 2001; Dalal 2002) that is capable of providing the ability (Langlois 1992; Stiller 1997; Sanchez 1999; McDysan 2000; Schilling 2000) to customize services for users and upgrading them when better components, with competitive advantages, come along.

Competitive pressures are forcing wireless service providers to streamline their business and technology strategies to offer more and better services to their customers. Wireless operators around the world are in the process of modifying their networks to offer *3G* services to subscribers. They are moving from simple voice and data services to high-speed value-added services (Carsello 1997; Garg 2001). These new services require upgrading existing 2G wireless networks. Current 3G standards, WCDMA and cdma2000, are incompatible, but technical efforts are being pursued to allow global roaming in future 4G networks.

The US wireless industry permits the coexistence of multiple, competing technologies to give choices to consumers. One of the US wireless market characteristics is that one service provider can differentiate itself from other competitors by choosing a particular technology for its network. For example, service providers tended to choose the TDMA standard when they moved from large 1G (AMPS) networks because they could provide consumers with high service reliability, more geographic coverage, and smooth migration. So, the US wireless market is a good case to analyze a firm's behavior when analyzing their strategic options among the next generation network technologies.

1.1.3 Real Options and Strategic Technology Management

Although real options constitute the capital investment analogue to financial options (Trigeorgis 1987), real options represent a relatively new approach to capital budgeting and resource allocation. Real options allow management to evaluate alternative strategies using traditional financial option pricing theory applied to the real assets or projects (Kulatilaka 1988). The real options approach (ROA) provides a structure linking strategic planning and financial analysis tools to evaluate potential opportunities and uncertainty (Dixit 1994). For example, when managers evaluate new projects, they may face several choices beyond simply accepting or rejecting the investment. Other choices include delaying decisions until the market conditions are more favorable, or deciding to start small and expanding later if the results are good.

Technology has emerged as an important competitive consideration for businesses (Abell, 1980). Since a firm's strategy is primarily concerned with how its products and services compete in the market, technology is among the most prominent factors that determine the rules of competition (Porter, 1983). With this in mind, the key strategic questions become

1) what is the role of technology in a firm's business strategy and
2) how can a firm's technology and business strategy be integrated most effectively?

As Porter (1985) points out, technology has an impact on every internal activity in a firm's value chain, and technologies can affect the industry structure or a firm's ability to differentiate and gain a competitive advantage. Hence, it is important for managers to track the evolution of all the technologies that affect the firm's value activities. Designing a technology strategy requires that the firm decide how each technology can be used to its competitive advantage (Porter, 1985) and whether a given technology should be developed in-house or outsourced.

Recently ROA has emerged in a strategic field because firms are often faced with higher degrees of uncertainty when making strategic investment decisions (Sanchez 1995). Using ROA is appealing to the firms because of its distinctive ability to capture managers' flexibility in adapting their future actions in response to evolving markets or technological conditions. So, ROA may be a useful tool for a firm's strategic technology management.

The traditional ROA has typically focused on the issues concerning business investment decisions, such as mining (Brennan 1985), oil (Paddock 1988; Pickles 1993; Dias 1999), medicine (Micalizzi 1996), and other investment activities (Kemma 1993; Flatto 1996; Benaroch 1998; Deng 1998; Kellogg 1999; Stonier 1999). However, this study directly assesses the value of technology itself, especially wireless network technologies (e.g., AMPS, *GSM*, *CDMA*, *WCDMA*, *cdma2000*, etc.).

1.2 MOTIVATION, GOAL, AND ISSUES

As technological uncertainty (Dosi 1982) in the US network industry increases, technological flexibility (Trigeorgis 1996; Levitas 2001; Bloom 2002) has become more important for network service providers to gain competitive advantage. Although the notion of real options has recently received some attention in network industries, its potential value still remains uncertain and its emphasis on technological flexibility is only loosely related to the goal of creating value in existing networks. So, we need better explanatory models for the value of technological flexibility in networks.

The US wireless industry is currently undergoing a major transition from the second generation (*2G*) to the third generation (*3G*), which will allow wireless network service providers to offer high speed wireless data services. So, each service provider must choose a particular transition strategy, indicating when, how, and at what pace to introduce new technologies. The chosen strategy will determine the service provider's focus and needs for the coexistence of the new and existing network technologies.

Since the complete replacement of the existing wireless network architecture is not practical and there is an economic trade-off when choosing among different technologies, the migration of the existing networks is challenging to network service providers. In other words, what is the best migration path to take and what do you do once you get there to sustain the essential competitive advantage under severe competition?

At present, there are several alternative wireless network technologies, including *TDMA*, *GSM*, CDMA, GPRS, EDGE, *WCDMA*, and *cdma2000*. (Rapport 1996; Carsello 1997; Prasad 1998; Garg 2001; Dalal 2002). Concerning wireless technology strategic decisions, two issues need to be addressed. One is the short-term issue of individual technology choice via the direct comparison of two technologies. For example, a 1G carrier can simply choose between the available 2G alternatives without considering its long-term direction. Another is the issue of considering the future evolutionary path from a long-term perspective. For example, currently there are two distinctive evolutionary paths to *3G* from the principal *2G* technologies, *GSM* and *CDMA*. One calls for substantial infrastructure replacement, while the other calls for upgrades to existing equipment.

This study proposes a theory to show technology options to migrate to new technology from old technology using the real options approach (ROA). We also develop a model to assess explicitly the value of technology transition options (i.e., technology choice) on a firm's technology strategy in the wireless industry.

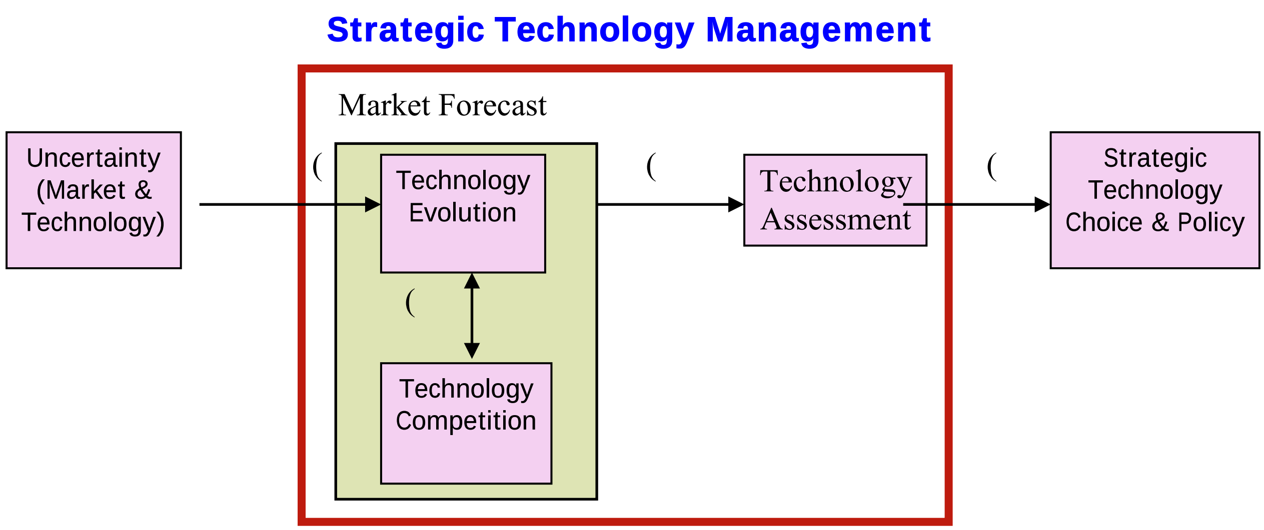
Hence, the goal of this study is to develop a theoretical framework for wireless network service providers to support their strategic decisions when considering technology choices as they move to the next generation network architectures.

1.3 RESEARCH FRAMEWORK

The main theme, '*The Real Options to Technology Management*', introduces a new perspective on technology management and policy issues, such as network architecture and technology choice, network service provisioning, and network regulation and policy. Based on ROA, wireless network service providers may find it worthwhile to evaluate new technologies as a strategic option.

The purpose of this study is not to give an absolute value for the choice of technology, but to provide a theoretical framework for supporting wireless network service provider's strategic decisions by quantifying the value of technology as a basic element of its decision-making. This study intends to raise core issues concerning the transition to *3G* and to resolve these both qualitatively and quantitatively.

Figure 1.1 shows the research roadmap of this study. Currently, the wireless network industry is facing high uncertainty in markets and technologies, such as the increasing demands for multimedia services and also the rapid change of their technologies. To manage this uncertainty, strategic technology management is required to gain competitive advantages. This process includes technology evolution, technology competition, and technology assessment. Technology evolution involves the analysis of past technology trends and identifies their characteristics. Next, technology competition is considered to forecast future technology trends. Based on the results of the above two processes, technology assessment is then performed to determine the best strategic options from a quantitative standpoint. Finally, the strategic technology choice and policy (i.e., the technology migration path) can be established.



① : Network Effect and Substitution Effect (Loglet Analysis)
(: Competition Effect (Sensitivity Analysis)
③ : Intra-generational and Inter-generational migration (Real Options Approach)
(: Strategic Technology Choice and Policy

Figure 1.1 Research Framework

As presented in Figure 1.1 and briefly discussed before, the research procedure for this study includes four stages: technology evolution, technology competition, technology assessment, and technology strategy and choice. Each stage includes the following tasks:

- **First Stage: Analysis of Technology Evolution**

  This study begins by the overview of market and technology trends in the world and US wireless industry including the characteristics of market and technology evolution in wireless network industry.

  The wireless market is analyzed by indicating market size and market share of each technology, and by separating each technology's market share using the *Loglet Analysis* techniques. Wireless technology evolution is investigated by presenting the historical evolution of wireless network technologies, i.e., the transition from first generation (*1G*) analog, voice-only communications to second generation (*2G*) digital, voice and data communications, and, further, to third generation (*3G*) wireless networks and the Internet.

The following propositions are presented:

Proposition 1: The evolution of wireless technologies has followed the traditional logistic S-curve pattern, but there exists a network effect because of technology standards and cost issues.

Proposition 2: The advent of new wireless technology will reduce the market demand for old wireless technology under conditions of uncertainty.

- **Second Stage: Sensitivity Analysis of Competing Technologies**

Two typical network architecture-based migration alternatives are suggested, specifically, the Global Systems for Mobile Communications (*GSM*)-based network scenario and the Code Division Multiple Access (*CDMA*)-based network scenario, as technology options for facilitating the migration into the next generation network architecture. One scenario calls for substantial infrastructure replacement (*architectural innovation*), while the other calls for upgrades to existing equipment (*modular innovation*).

In this study, the basic model for the analysis of competing technologies toward 3G networks is 50-50 market share between two technologies. Then, two extreme cases are analyzed as sensitivity analysis: one is the GSM-based network dominance scenario and the other is the CDMA-based network dominance scenario.

The following propositions are discussed:

Proposition 3: The 3G wireless market, with competing WCDMA and cdma2000, will be efficient, if each technology has 50% market share.

Proposition 4: The 3G wireless market, with competing WCDMA and cdma2000, will not be efficient, if each technology dominates in the market.

- **Third Stage: Assessment of Technology Transition/Migration**

The concept of real options gives management the opportunity to respond to changing circumstances as it pursues a certain strategy. This study introduces ROA to assess the technology migration path that optimizes *3G* wireless data service network architecture design.

Based on the real options approach (ROA), strategic technology option model (STOM) is developed as an assessment technique of network technologies. This model attempts to show explicitly how technology choices (or options) affect the network value by dealing with technological uncertainty. As addressed earlier, STOM will be used to assess simple technology comparisons (short-term perspective) and evolutionary paths (long-term perspective).

The following propositions are presented:

Proposition 5: Wireless technology transition between generations (Intra-technology transition) will be desirable.

Proposition 6: Wireless technology transition across generations (Inter-technology transition) will be desirable.

- **Fourth Stage: Establishment of Technology Strategy**

  Strategic options are identified for evolving towards the next generation network architecture and alternative migration strategies are presented. However, one technology or migration path is not recommended over another in this stage. Rather, the pros and cons that operators may face in deploying new technology are identified and discussed.

  A case study focuses on the US wireless industry and major US wireless carriers to analyze their strategic decisions for the choice of network architecture and technologies. Technology strategy is discussed in the world industry level, US industry level, and US major carrier level to establish technology strategy.

  The following propositions are presented:

  Proposition 7: Strategic technology options create value in networks.

  Proposition 8: A firm's technology strategy (choice and policy) will be influenced by industry standards and government policy.

Consequently, this study contributes to management ability to rethink their network provisioning activities in terms of the available network technology options and to maximize overall gain in networks in highly uncertain environments. It also will give "*Options Thinking*" to network managers as a strategic tool linking network engineering and financial strategy; for example, network technology choice is not simply a network engineering issue, but also a strategic management (investment) issue.

1.4 STRUCTURE OF DISSERTATION

The remainders of the study are organized as follows:

- Chapter 2 is an overview of real options including the notion of real options, the comparison with financial options, the types of real options, mathematical methodologies, and applications. Although the fundamental importance of *Real Options* in academics and in practice has been recognized, the dynamics and flexibility that this approach incorporates into the problem solving process has not been fully realized.
- In Chapter 3, the market characteristics of wireless industry and the historical evolution of network technology are described. Network effect and substitution effect are introduced as market characteristics of wireless industry. Technology evolution is explored wireless technologies in generations, for example, first generation (1G), second generation (2G) and third generation (3G) technologies.
- In Chapter 4, based on the real options theory, strategic technology option model (STOM) is developed. STOM is a model for assessing the effect of switching wireless network technologies, for example, towards the *3G* from *2G* mobile communication system architecture.
- Chapter 5 presented modeling and methodology to assess technology options in the wireless industry. Modeling includes technology options in wireless networks and constructs a simple market structure. *Loglet Analysis* method is used to forecast future wireless markets including 3G market. Model validation is also explored using graphical residual analysis as well as confidence interval statistic.
- Chapter 6 presented the results of the assessment of technology options and discussed their implications in the perspective of policy makers.

- Finally, Chapter 7 summarizes the study and discusses the limitations of this study and future research in a brief.

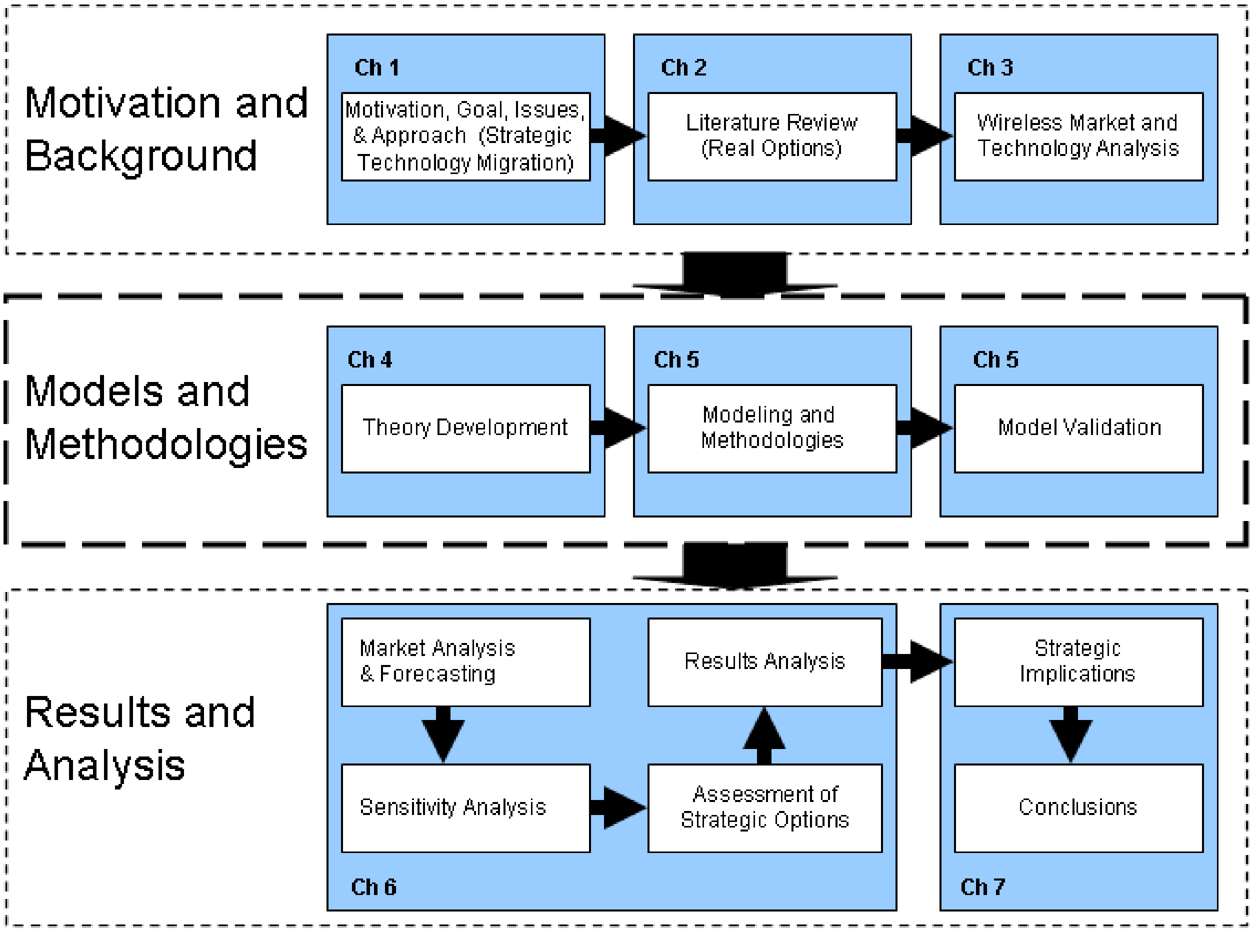


Figure 1.2 Research Workflow

2.0 REAL OPTIONS: AN OVERVIEW

Real options have emerged from the criticism of the traditional investment evaluation approaches, such as payback, net present value (NPV), internal rate of return (IRR), profitability index (PI), and accounting rate of return (ARR), because of lacking the dynamic element that real options offer (McDonald 1986; Kulatilaka 1988; Pindyck 1988; Dixit 1994; Trigeorgis 1996). Then, what are the problems of the traditional approaches? Let's take a look at NPV method (Dixit 1994), one of the most popular tools in investment analyses. The NPV of an investment is the present value of the difference between the expected stream of profits and the expected stream of expenditures. An investment opportunity is acceptable if its NPV is greater than or equal to zero. However, NPV ignores the opportunity cost of making a commitment now and giving up the option of waiting for new information (Pindyck 1988). NPV also does not consider irreversibility of investment and it does not allow for postponement of investment decisions.

Furthermore, conventional approaches assume implicitly that an investment will be undertaken now and will continue on a set scale (i.e., a single cash flow) until the end of its expected useful life, even though the future is uncertain. They also ignore the added value brought to the project through the flexibility of management to make operating decisions during the life of the project according to changes in market conditions over time(Trigeorgis 1996). For example, management may postpone a project until market conditions are more desirable to improve returns. Similarly, the choice to abandon a project during its life may be valuable because it can decrease losses.

The limitations of the traditional approaches have important implications:

First, unlike the traditional approaches, uncertainty is not always a negative, high-risk consideration, but a potentially positive consideration from the perspective of options theory (Trigeorgis 1996). When a future decision depends on the source of uncertainty, uncertainty creates opportunity as the range of possible outcomes. Managers should welcome, not fear this uncertainty. Managers try to view their markets in terms of the source, trend, and evolution of uncertainty; and then determine the degree of investments to best take advantage of uncertainty.

Second, investments are optional with dynamic, ever-changing characteristics (Paddock 1988). Managers intuitively can use options, such as when they delay completing an investment until the results of a pilot project are known. The decision about whether to complete the investment program is a contingent investment decision, one that depends on an uncertain outcome.

Third, a negative NPV does not necessarily mean that an investment should be abandoned and a positive NPV is not sufficient to warrant immediate investment (McDonald 1986). An option provides the *right* to make an investment in the future, without a symmetric *obligation* to make that investment. Because an option can have a positive payoff but need never have a negative one, an option has always a positive present value.

Since the traditional approaches are inadequate as strategic management tools (Trigeorgis 1987), the need for a better analysis technique is the motivation for this discussion of real options. Instead of using the NPV rule, Dixit and Pindyck (1994) advocate the real options approach to improve the accuracy of analyses and explicit consideration of flexibility, which they have narrowly defined as postponement of decisions. Likewise, when dealing with business decisions involving real assets, such as construction projects, equipment acquisitions, etc., decision makers must consider real options available and the potential risk involved with each.

2.1 BASICS OF OPTIONS

To appreciate how and why ROA is likely to effect fundamental changes in the way practitioners do strategic decisions, it is necessary to understand the basic concepts of options.

An option is well developed for financial markets, such as stocks and bonds. A financial option is one of derivative securities, which are financial instruments whose value depends on the price of an underlying asset (Cox 1979; Chris 1997; Rubash 1999). An option (warrant) is a contract which gives its holder the right but not the obligation to buy (call option) or sell (put option) an asset at a pre-specified price and date (Brigham 1998). We make our discussion on the base of a stock option. That is, having rights without obligations has financial value, so option holders must purchase these rights, thus making them assets.

Standard financial option contracts on securities include calls and puts (Chris 1997). A European call contract grants its owner the right, but not the obligation, to purchase a specified quantity of security at a specified price on or a specified date (the expiration date). A European put contract grants its owner the right, but not the obligation, to sell a specified number of stocks at the strike price on or the expiration date. If the option can be exercised prior to its expiration date, then it is called an American (call or put) option. The types are summarized in Table 2.1.

Table 2.1 Types of Financial Options

Classification	Right to buy	Right to sell
Exercise only on expiration date	*European Call Option*	*European Put Option*
Exercise at any time	*American Call Option*	*American Put Option*

The value of an option can be divided two parts: the intrinsic value and the time value (Rubash 1999). The intrinsic value of a call is given by the maximum of either the difference between security price and strike price or zero. The intrinsic value of a put is the maximum of either the difference between strike price and security price or zero. Both call and put are directly related to their time to expiration and the price volatility. These two parameters add the time value to the option's intrinsic value to arrive at the overall option value.

The option is said to be "in the money" when its intrinsic value is strictly positive, "at the money" when the intrinsic value is zero, and "out of the money" when the intrinsic value is strictly negative (Brigham 1998). Figure 2.1 displays a graph of payoff at expiration for call and put options. An option payoff is the amount you get if you exercise the option.

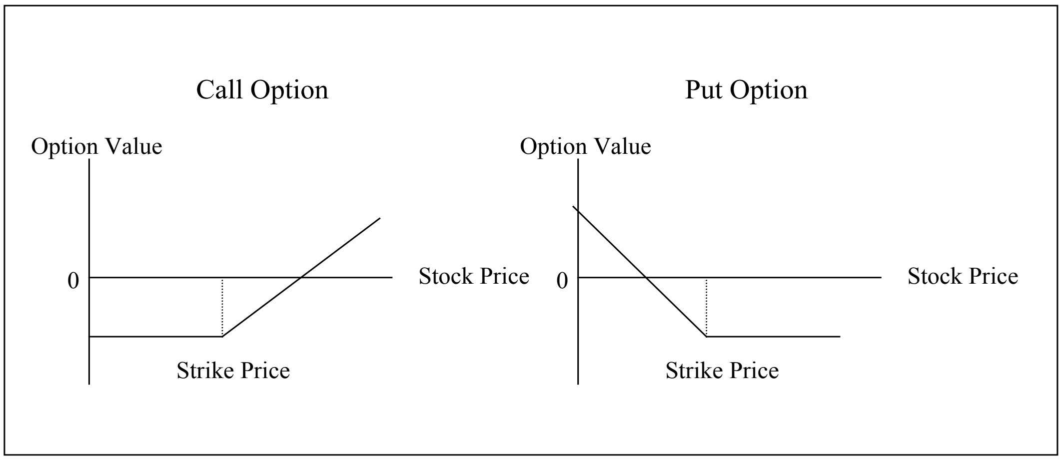


Figure 2.1 Payoff of a Call Option and a Put Option (Brigham 1998)

2.2 REAL OPTIONS

2.2.1 Concepts

As addressed in the previous, the traditional approaches for valuation of capital investment just do not work for current new business realities, which are strategic investments with many uncertainties and fast changes. If new information arrives continuously, and it is possible to postpone the investment decision until some of the future uncertainty is resolved, there is an option value associated with waiting to invest, in postponing the incurring of the investment component. The value of waiting to invest (McDonald 1986; Pindyck 1988; Kemma 1993; Dixit 1994) into a value maximizing investment decision is the option to wait value or the opportunity cost of investing now, rather than waiting and keeping open the option investment opportunity.

Dixit & Pindyck (1994) (Dixit 1994) defined *real options* as opportunities to respond to the changing circumstances of a project. These real options represent change scenarios available to management, but not obligations to change unless management decides the change is warranted or desirable. Real options give management access to significant upside potential while minimizing the downside losses and thereby optimizing those options with the greatest volatility (Pindyck 1988). They are differentiated from financial options because they involve real assets rather than financial assets.

Real options are common business opportunities that invest in something today to create an opportunity in the future (Flatto 1996). The real option approach (ROA) creates a decision discipline that emphasizes learning and proactive choice (Levitas 2001). To get started, managers need to transform this immediately intuitive concept into a workable methodology.

2.2.2 A Brief History

The Black and Scholes (1973) and Merton (1973) studies are roots of the options paradigm. Their assumptions are that options trading and decision making take place in tandem and that 'Brownian motions' of unpredictability, or random walk in financial markets apply. They developed the technique of risk-neutral, or equivalent martingale, pricing mechanism. Later it formalized by Cox and Ross (1976), Constantinnides (1978), Harrison and Pliska (1981), and others. Their implication is that if the expected rates of change in the underlying cash-flow drivers or stochastic state variables are risk-adjusted, the resulting cash flows can be discounted at the risk-free interest rate, regardless of the types of future decision contingencies.

Although the concept of real options has been applied to managerially-important decision by Myers (1977) and Kester (1984), Brennan and Schwartz (1985a, b) and McDonald and Siegel (1986) were the first to actually employ these insights, now known as *Real Options*, in the valuation of real assets in project evaluations.

The studies of natural-resource industries including mining, petroleum, real estate development, farming, paper products, have been popular, such as Titman (1985), McDonald and Siegel (1986), Trigeorgis and Mason (1987), Paddock et al. (1988), Ingersoll and Ross (1992), and Quigg (1993). R&D-intensive industries (i.e., pharmaceuticals), long-development capital intensive projects (e.g. large scale construction or energy generating plants), and startup ventures are also popular, such as Maid and Pindyck (1987); Carr (1988); Trigeorgis (1993). Later, Dixit and Pindyck (1994), Smith (1995), and Trigeorgis (1996) deal with the issue of the timing of investments when there is competition in product markets.

The game-theoretic real options approach has been emerged. Because the cash flows from an investment project are influenced not only by agents within the firm who can react as new information becomes available, but also by the actions of agents outside the firm, such as competitors and suppliers. Dixit (1989) and Williams (1993) were among the first to consider real options within an equilibrium context as a game, although not all take an explicitly game-theoretic perspective. More explicit game-theoretic approaches can be seen in Trigeogis (1991), Smit & Ankum(1993), Smit & Trigeogis(1993), Trigeorgis(1996), Grenadier(1996), and others.

2.2.3 The Analogy between Financial Options and Real Options

While financial options are detailed in the contract, real options embedded in strategic investments must be identified and specified (Amram 1999). The emerging field of real options applies theory to real projects. Future decisions have features similar to financial options. Real options will correct deficiencies in the traditional analysis and will detail these deficiencies shortly and will also consider potential drawbacks to real options.

The major difference between financial options (e.g., stock options) and real options is that real options are applicable to real assets (Dixit 1994). A real asset is usually something tangible, such as a factory, car, etc., while a financial asset typically consists of stocks, bonds, currency, etc. Some financial options solutions may be useful in the real investment context with some relevant adaptations and parameters using financial analogies. The return from an investment, like the return from a stock, comprises the capital gain and the dividends. Over time, the expected rate of return from a real investment is equal to the sum of the expected growth rate plus the convenience yield of the underlying commodity. The expected rate of return corresponds to the risk-adjusted discounting rate of financial market models like the CAPM (Capital Asset Pricing Model).

However, we cannot simply apply the theory of financial options to the field of real options, because of some important differences in the orientation of the two fields, as outlined in the following discussion.

First, typically financial options are typically short-lived (less than one year to expiry), while real options are long-lived, and some have no expiry date.

Second, financial options are written on underlying assets that are traded in various markets. The traded assets cannot have a negative price. In real options, the underlying asset can be a notional asset that is not traded, so there is nothing preventing its price from being negative. Usually there is no observable market price for the underlying asset of real options because real options do not refer to traded assets.

Third, financial options are generally quite simple in the sense that they involve a simple option with a single exercise price. However, the exercise price of real options may vary over time and, indeed, may be randomly. Frequently there may be several real options with the same underlying asset. For example, performing R&D creates an option to adopt a technology with unknown benefits. If the R&D is successful, there is a subsequent option to expand the product line. While the product becomes obsolete, there is the option to abandon. So the R&D option will include the value of the subsequent expansion and abandonment options.

Table 2.2 Comparison of variables on financial and real options (Flatto 1996)

Financial Options	Real Options
Current value of financial derivatives	Present value of expected cash flows
Exercise price	Investment cost
Time to expiration	Time until opportunity disappears
Financial derivatives uncertainty	Project uncertainty
Riskless interest rate	Riskless interest rate

2.2.4 Types of Real Options

Real options provide management with valuable flexibility in its decision making process. This real option flexibility can be categorized as waiting, staging, changing, abandoning, switching, and growing (Trigeorgis 1996).

First, waiting to invest (McDonald 1986; Ingersoll 1992) occurs when you can put off a decision until some date in the future. This allows management to determine if resources should be spent on a project at a future date. Since early investment implies sacrificing the value of the option to wait, this option-value loss is like an additional investment opportunity cost. The option to wait is particularly valuable in resource extraction industries (Paddock 1988), such as farming and paper products (Tourinho 1979) and real estate development (Titman 1985; Williams 1991; Capozza 1994), because of the high uncertainties and the long investment issues.

Second, staging option (McDonald 1985; Maid 1987; Carr 1988; Trigeorgis 1993), which is called the option for time-to-build investments, occurs in a series of outlays that allows the project to be abandoned in mid-stream if conditions become unfavorable. Each stage can be viewed as an option on the value of subsequent stages by incurring cost outlays required to proceed to the next stage. The staged option is valuable in all R &D-intensive industries, especially pharmaceuticals (Kolbe 1991) ; in highly uncertain, long-development, capital-intensive industries, such as energy (Mason 1988) and the construction industry (Ofori 1991); and in venture-capital financing (Sahlman 1988; Wilner 1995).

Third, the option to change includes the option to expand and contract or to shutdown and restart. This option will be exercised only if market development becomes favorable. If market conditions turn weaker than expected, the company can reduce the planned investment outlays. Therefore, the rate of expenditure can be adjusted according to market conditions at a particular time. Buying undeveloped land (Trigeorgis 1987) and building a small plant in a new geographic location (Pindyck 1988) could be examples of the option to change scale.

Fourth, abandoning (Kulatilaka 1988; Myers 1990) may allow the company to discard a project if market conditions change unfavorably. Then, the company can sell any assets available to offset the loss on the second market. Abandonment options are generally found in capital-intensive industries (Myers 1990), such as airlines and railroads, in financial services (Kensinger 1987), and in new-product introductions.

Fifth, the option to switch (Margrabe 1978) allows an organization to change either the input mix or the output mix of a facility. If environmental conditions change, this option provides the flexibility to alter either the process or product. Switching options are considered for small batch operations that are subject to volatile demand, such as consumer electronics, toys, machine parts, and autos, and feedstock-dependent facilities, electric power (Tseng 1999), crops, and chemicals.

Sixth, the option to grow (Venezia 1979; Kester 1984; Wilner 1995) is used when an investment is required for further development. A company may invest in R&D even though it typically has a negative value because of the future growth value of that R&D. Growth options are found in infrastructure-based or strategic industries, such as high technology, in R&D operations (Kulatilaka 1988), and in multinational operations.

2.3 MATHMATICAL MODELING

Real options can be valued much the same as financial options. Option pricing models such as the Black-Scholes model or the Cox/Ross/Rubinstein binomial model can be applied to real options. Recently Baldwin and Clark's model was introduced.

2.3.1 Black-Scholes Option Pricing Model

Researchers have made a lot of efforts for developing methods for determining the value of options. The best known result is the Black-Scholes Model. The Black-Scholes option pricing model (B&S) was produced as a solution for pricing European style call options on stock in 1973. The B&S is used to measure both the value and risk of an option in relation to its underlying stock. It is used in continuous time.

The following are assumptions made for the derivation of the Black-Scholes formula:

- Financial markets are frictionless: no taxes or transaction costs, all assets are perfectly divisible, and no restrictions on short sales
- The stock pays no dividends within the time period under consideration
- The interest rates for borrowing and lending are the same and constant for the period considered
- The stock price follows a log-normal process: for example, the stock price follows a continuous path, the return over any period is independent of the return over any other period, the returns over two different time periods with the same time interval

are identically distributed, and the continuously compounded return over any period is normally distributed (which is a consequence of the other assumptions)

The above assumptions lead to a formula which enables the estimation of the real value of the option considered. A number of researchers (e.g. Merton) have tried to lift some of the simplifications introduced in the Black-Scholes model and have come up with some other equations for valuing options. However, these derivations are based themselves on assumptions so that it can be claimed that there is no unique formula which is able to determine the exact value of an option.

As shown in Figure 2.3, the model captures the option value determinants in a single simple equation. The convenience of having a formula which is easy to evaluate comes at the expense of losing accuracy.

There are the five parameters essential to the pricing of an option: the underlying stock price, the strike price, the time to expiration, the volatility of the stock, and the prevailing interest rate.

- First, *the underlying stock price (S)* is the value of the option is going to be very dependent on the value of the underlying stock.
- Second, *strike price (X)* is that the option is the right to buy the stock at a certain price, i.e., the strike price, also known as the exercise price.
- Third, *the time to expiration (t)* is a measure of the time left until the expiry of the option.
- Fourth, *the volatility of the underlying stock (σ)* is a measure of how volatile the underlying stock is. σ is a very important factor in the option price.
- Fifth, *the prevailing interest rate (r)* is the interest rate prevailing for time deposits with the equivalent maturity of the option. For example, if the option expires in 3 months' time, then *r* is the 3-month interest rate.

The Model:

$$C = SN(d_1) - X\,e^{(-rT)}\,N(d_2)$$

C = Current Value of the Call Option
S = Current Stock Price
t = Time until Option Expiration
X = Option Striking Price
r = Risk-free Interest Rate
N = Cumulative Standard Normal Distribution

e = Exponential Function (2.71828)

$$d_1 = \frac{Ln(S/X) + (r + \sigma^2/2)^t}{\sigma\sqrt{t}}$$

$d_2 = d_1 - \sigma\sqrt{t}$

σ = Standard Deviation of Stock Returns
ln = Natural logarithm

Figure 2.2 Black-Scholes Option Pricing Model (*Kevin Rubash, 1999*)

The first part of the model, SN(d1), is the present value of receiving the stock if it finishes above the strike price at expiration. This is found by multiplying stock price [S] by the change in the call premium with respect to a change in the underlying stock price [N(d1)]. The second part of the model, Xe(-rt)N(d2), is the present value of having to pay the strike price under the same condition. The fair market value of the call option is then calculated by taking the difference between these two parts. Indeed, if the stock finishes below the strike price at expiration of the call, then the call is worthless, but if it finishes above the strike price, then the call holder has to pay the strike price and will receive the stock in exchange.

Charts of the Black-Scholes Model show the relationship between a call's premium and the underlying stock's price. The graph (Figure 2.4) identifies the Intrinsic Value, Speculative Value, Maximum Value, and the Actual premium for a call.

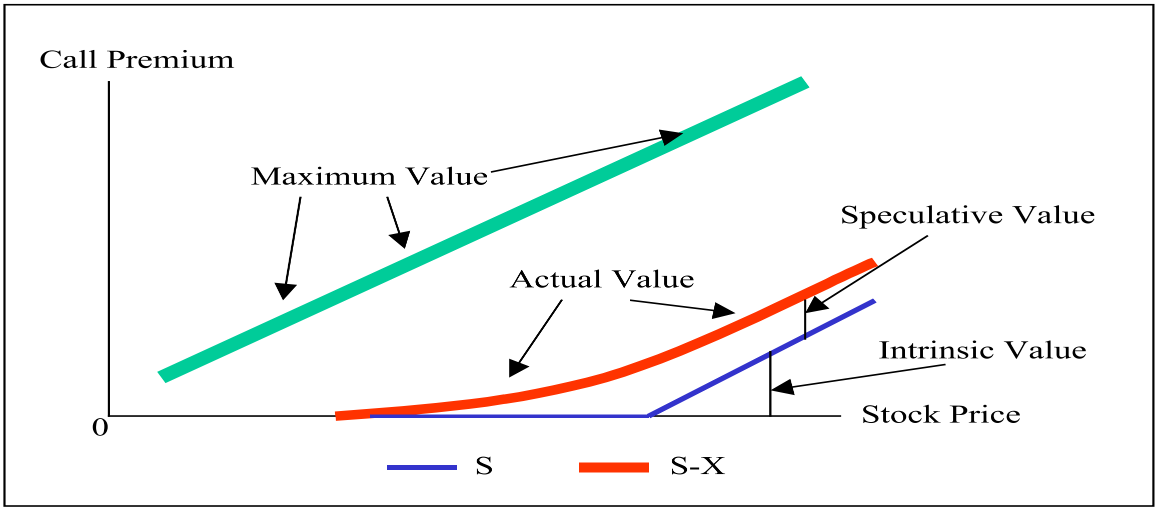


Figure 2.3 Call Premium vs. Security Price (Kevin Rubash, 1999)

The intrinsic value represents the "now or never" case (NPV). The speculative value shows the option value (premium) for waiting to the expiration of the rights. Actual value is the intrinsic value (NPV) plus the speculative value (the option premium). The maximum value is the ideal value possible to achieve in case the option period is unlimited.

2.3.2 Binomial Option Pricing Model

Even though the Black-Scholes option pricing model was introduced in 1973, it is worthwhile to explore a simpler derivation of option price developed by Cox, Ross, and Rubinstein in1979 based upon a stochastic binomial process. The binomial approach is used to analyze finite-lived options in discrete time. It allows great flexibility in modeling various stochastic processes for the present value of future benefits and variation of conversion costs over time.

The rate of return on the stock over each period can have two possible values: u with probability q, or d with probability 1-q. Thus, if the current stock price is S, the stock price at the end of the period will be either uS or dS . This model also assumes that the interest rate is constant. We may borrow or lend as much as we wish at this rate. We will continue to assume that there are no taxes, transaction costs, or margin requirements.

Let C be the current project value, C_u its value at the end of the period if the project value goes to uS, and C_d its value at the end of the period if the project value goes to dS. Since there is now only one period remaining in the life of the call, we know that the terms of its contract and a rational exercise policy imply that C_u=max[0, uS-X] and C_d=max[0, dS-X]. Therefore,

C → C_u= max[0, uS-X] with probability q,

C → C_d= max[0, dS-X] with probability 1-q.

Suppose we form a portfolio containing Δ shares of stock and the dollar amount B in riskless bonds. This will cost $\Delta S+B$. Since we can select Δ and B in any way we wish, suppose we choose them to equate the end-of-period values of the portfolio and the call for each possible outcome. This requires that

$$\Delta uS + r\,B = C_u \text{ and } \Delta dS + r\,B = C_d.$$

Solving these equations, we find that

$$\Delta = \frac{(C_u - C_d)}{(u-d)S} \quad , \quad B = \frac{(uC_d - dC_u)}{(u-d)r}$$

With Δ and B chosen in this way, we will call this the hedging portfolio.

Summing up all of this, we conclude that if there are to be no riskless arbitrage opportunities, it must be true that

$$\begin{aligned} C &= \Delta S+B \\ &= \frac{(C_u - C_d)}{(u-d)} + \frac{uC_d - dC_u)}{(u-d)r} \\ &= \frac{\{[\frac{(r-d)}{(u-d)}]C_\mu + [\frac{(u-r)}{(u-d)}C_d]\}}{r} \\ &= \frac{[pC_u + (1-p)C_d]}{r} \end{aligned}$$

when $p \equiv (r\text{-}d)/(u\text{-}d)$ and $1\text{-}p \equiv (u\text{-}r)/(u\text{-d})$

if this value is greater than S-X, and if not, $C = S$-X

We now have a recursive procedure for finding the value of a call with any number of periods to go. By starting at the expiration date and working backwards, we can write down the general valuation formula for any n:

$$C = \frac{\{\sum (\frac{n!}{j!(n-j)!}) p^j (1-p)^{n-j} \max[0, (u^j d^{n-j} S - X)]\}}{r^n}$$

This gives us the complete formula, but with a little additional effort we can express it in a more convenient way. Let a stand for the minimum number of upward moves which the stock must make over the next n periods for the call to finish in-the-money. Thus a will be the smallest non-negative integer such that $u^a d^{n-a} S > X$. By taking the natural logarithm of both sides of this inequality, we could write a as the smallest non-negative integer greater than $\log(X/Sd^n)/\log(u/d)$.

For all $j<a$, $\max[0, u^j d^{n-} S-X]\}=0$, and for all $j \geq a$, $\max[0, u^j d^{n-j} S-X]\}= u^j d^{n-j} S-X$. Therefore,

$$C = \frac{\{\sum (\frac{n!}{j!(n-j)!}) p^j (1-p)^{n-j} \max[0, (u^j d^{n-j} S - X)]\}}{r^n}$$

Of course, if $a>n$, the call will finish out-of-the-money even if the stock moves upward every period, so its current value must be zero. By breaking up C into two terms, we can write the following:

$$C = S[\sum (\frac{n!}{j!(n-j)!}) p^j (1-p)^{n-j} (\frac{u^j d^{n-j}}{r^n})] - Xr^n [\sum (\frac{n!}{j!(n-j)!}) p^j (1-p)^{n-j}]$$

Now, the latter bracketed expression is the complementary binomial distribution function $\Phi[a;\, n,\, p]$. The first bracketed expression can also be interpreted as a complementary binomial distribution function $\Phi[a;\, n,\, p']$,

where $p' \equiv (u/r)p$ and $1- p' \equiv (d/r)(1-p)$.

p' is a probability, since $0 < p' < 1$. To see this, note that $p< (r/u)$ and $p^j (1-p)^{n-j} (u^j d^{n-j} / r^n) = [(u/r)p]^j\, [(d/r)(1-p)]^{n-j} = p'^j (1-p')^{n-j}$.

The generalized binomial option pricing model is shown in Figure 3.5.

$$C = S\Phi[a; n, p'] - Xr^{-n}\Phi[a; n, p],$$

Where C = Current call value

S = Current stock price

X = the option's exercise price

$\Phi[\,,\,,\,]$ = Complementary binomial distribution

p (the hedging probability) $\equiv (r-d)/(u-d)$ and $p' \equiv (u/r)p$,

$a \equiv$ the smallest non-negative integer greater than $\log(X/S\,d^{n})/\log(u/d)$

n = number of periods

If $a>n$, C = o.

Figure 2.4 the Binomial Option Pricing Model (Cox et al., 1979)

The formula means that the call option value (C) equals the current stock price (S) multiplied by a probability (Φ), less the present value of the option's exercise price (X) multiplied by another probability ($r^{-n}\Phi$). This result is similar to that of the Black-Scholes option pricing model.

2.3.3 Baldwin and Clark's Model

Baldwin and Clark (2000) developed a model to value modularity using the real options approach. Their theory is based on the idea that modularity creates value. At one extreme, a non-modular system (i.e. a fully integrated system) has only one option, which is to replace the whole system, even if only with an incrementally better version, or to leave the old one. In contrast, a modular design creates many options. It isn't necessary to take an all-or-nothing approach. A system of independent modules can be kept as is, or any or all modules can be replaced independently. Thus, a modular design process creates at least as many options as there are modules. The value of modular system is calculated by adding up the net option value (NOV) of each module:

$$V = NOV_1 + NOV_1 + ... + + NOV_n$$

The NOV is the expected payoff of modularity, accounting for both benefits and exercise costs.

$$NOV_i = \max_{ki}\{\sigma_i n_i^{1/2} Q(k_i) - C_i(n_i)k_i - Z_i\}$$

$\sigma_i n_i^{1/2} Q(k_i)$ is the expected benefit to be gained by accepting the best positive-valued candidate generated by partitioning modules and k_i independent experiments. For example, a module creates opportunities: (a) technical potential (σ_i), which is similar to the volatility (uncertainty) in financial option theory, (b) mix-and-match k_i experiments to create the best replacement candidate (Q(k)), (c) specialization or innovation by simplifying the complex networks ($n_i^{1/2}$). The second part, $Ci(n_i)k_i$, is the cost to run k_i experiments as a function C_i of the module complexity n_i. The last part Zi is the cost to replace the module given the number of other modules in the system that directly depend on it, the complexity n_j of each, and the cost to redesign each of its parameters. However, they ignore some important factors:

First, technical uncertainty (σ) is implicitly assumed to be a constant coefficient without considering technological innovation. In reality, technical uncertainty decreases because of the technology innovation.

Second, the effect of the loss of coordination (complementarity) by modularization is not reflected. However, it is very important factor in networks because most of network components are highly correlated.

3.0 WIRELESS MARKETS AND TECHNOLOGIES

This chapter presents a brief overview of wireless market with market share, the number of subscribers, services, and handset equipment environment. It also discusses the historical evolution of the various generations of wireless network architecture and technologies, such as *AMPS, TDMA, CDMA, GSM, GPRS, EDGE, WCDMA,* and *cdma2000*. Finally we discuss the characteristics of wireless markets and technologies.

Much has been debated about the development of wireless technologies, for example, whether a certain technology enhancement by adding platforms to existing networks or by upgrading existing platforms rather than discarding equipment is 'revolution' or 'evolution', respectively. However, this stdy does not focus on a specific technology development, but the broadly historical development of wireless network architecture and technologies. For example, wireless networks historically have been developed from analog to digital in technology, and from voice-oriented to data-oriented in network service architecture.

The main purposes of this chapter are to understand the development of wireless market and technology as background knowledge, and to explore it for predicting the future of wireless market and technology.

3.1 WIRELESS MARKET

3.1.1 World Market

World wireless market is growing rapidly.(CTIA 2003) (Standard&Poor's 2003) (EMC 2004) There are approaching 1.5billion wireless users worldwide -an increase of approximately 20% since 2001 with 500,000 new subscribers being added each day (UMTS 2002). While predictions vary, it is widely anticipated that the number of users worldwide may double to more than 2 billion until 2010 (EMC 2004). Asia boasts more wireless users than any other region, followed by Europe, North America, Latin America and Africa/Middle East (EMC 2004). *GSM* is the leading wireless technology standard in the world, in terms of number of operators and subscribers (GSM 2003). By the end of 2001, GSM is over 560 million subscribers, representing approximately 65% of the total wireless subscriber base in the world. As of 2002, GSM has the 89% of European market share, available in 195 countries with more than 500 network serving nearly one billion customers globally (UMTS 2002). However situation is very different in other regions of the world. Asia boasts the widest deployment of *CDMA* systems, thanks largely to Korea's investments in technology and *TDMA* is the most widely used second-generation technology in the western hemisphere (EMC 2004).

One of the most emerging services in wireless market is the explosive popularity and growth of non-voice services, such as Short Message Service (SMS) and Multimedia Messaging Service (MMS). Of this enormous market opportunity, it is anticipated that these data services are driving new revenues to network service providers as the largest revenue generators (MDA 2003). The increasing demands for new multimedia services and applications will also accelerate for network service providers to launch *3G* network architecture and technology.

Wireless handsets continue to grow: 423 million handsets were sold in 2002 – an increase of 6% from 400 million handsets in 2001 (Gartner 2003). In parallel with this continued growth, handsets are becoming more diverse and sophisticated with the addition of color screens, in-built cameras, PDA-like functions and high-speed data access (StrategyAnalytics 2003).

Figure 3.1 plots the number of subscribers in each wireless technology from 1990 to 2002. The world wireless market experienced high growth from the mid-1990's until 2001. However, in 2002, the growth rate was not as strong, and expectations are that it will level off in the next few years, given the current technologies and the nearly saturated subscriber base. *GSM* will continue to be the dominant world technology, primarily because it is the only standard in Europe, the leading wireless market. *CDMA* has experienced high growth in the limited Asian market and will become the primary competition for *GSM* in the future. *TDMA*, a technology used mainly in the USA, will eventually become obsolete as providers upgrade to more advanced technologies, such as *GSM* or *CDMA*. Analog technology will be completely phased out after 2004.

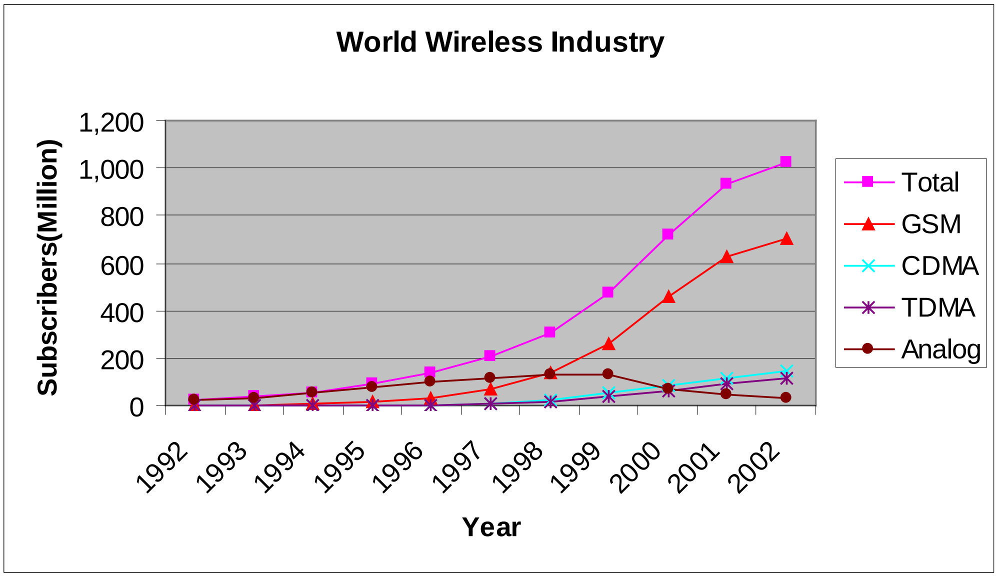


Figure 3.1 Market Size (Source: EMC, Paul Budde Communication)

Based on the number of subscribers in Figure 3.1, market shares for the various technologies are shown in Figure 3.2. Figure 3.2 provides a better picture of the relative size of world wireless market. The chart clearly shows the dramatic growth in *GSM* technology, while analog technology fades away. *CDMA* and *TDMA* have maintained their market shares in recent years.

These historical market share statistics are used in this study to estimate the market value of each technology for two reasons. First, a network's market value depends on the usage of networks, so the more the subscribers, the greater the market value, and vice versa. Another reason is that actual market data, such as revenues, costs, and the number of subscribers, is only available on an historical basis. So, this historical data is used for projection purposes.

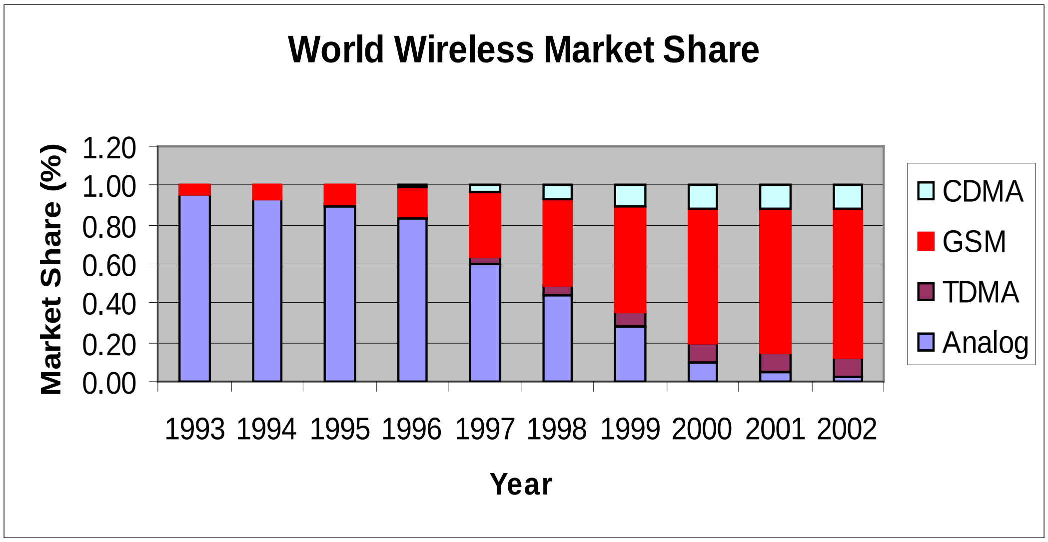


Figure 3.2 Market Share

3.1.2 US Market

The US wireless market is one of the largest mobile markets in the world, with an estimated 141.4 million cellular subscribers in December 2002 for its population of 286.9 million, nearly one mobile unit for every two Americans (Budde 2003). A year-end 2001 survey of the US's wireless industry from the Cellular Telecommunications and Internet Association (CTIA) reported record revenues, strong growth in subscriptions and an explosion in wireless minutes of use. Total service revenue increased by 22.6% in the second half of the year to $34.1 billion, to achieve total 2001 revenues of $65 billion. A significant leap forward was growth in wireless data, with revenues reaching $545 million in 2001 after only three years.(CTIA 2003)

Based on wireless revenues, the largest domestic operator in US is now Cingular-AT&T Wireless with over 40% US wireless market share, followed by Verizon Wireless (Bell Atlantic/GTE and Vodafone AirTouch's joint venture), Nextel Communications Inc. ($3.3 billion), and Sprint PCS ($3.2 billion) (Standard&Poor's 2003). The case of merger between Cingular and AT&T has taken the concept of 'co-opetition' (Budde 2003) to new levels as they battle on one front and make deals on another as two GSM-based major US wireless carriers.

Figure 3.3 plots the number of subscribers in each wireless technology from 1992 to 2002 in the US. Unlike GSM's dominant position in world wireless market, CDMA has experienced high growth and dominates US wireless market. TDMA also covers high market share, but will eventually obsolete as providers upgrade to more advanced technologies, such as GSM, GPRS, EDGE, and WCDMA. Analog will be completely phased out after 2004 in the US wireless market.

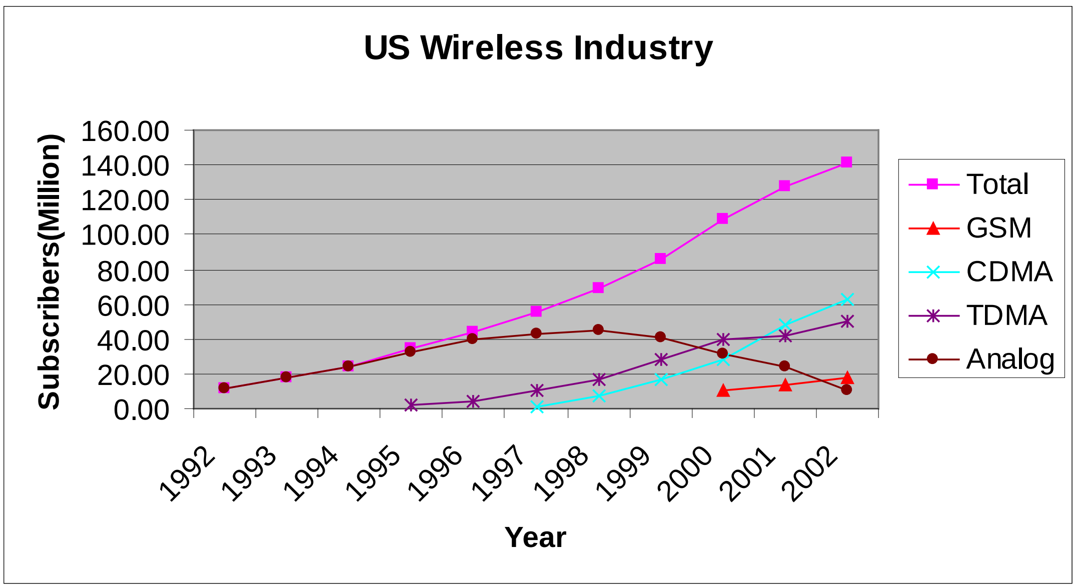


Figure 3.3 US Wireless Market Size (Source: FCC, CTIA, and EMC)

Figure 3.4 shows market shares for the various technologies. It provides a better picture of the relative size of US wireless market. The chart clearly shows the dramatic growth in CDMA and TDMA, while analog fades away.

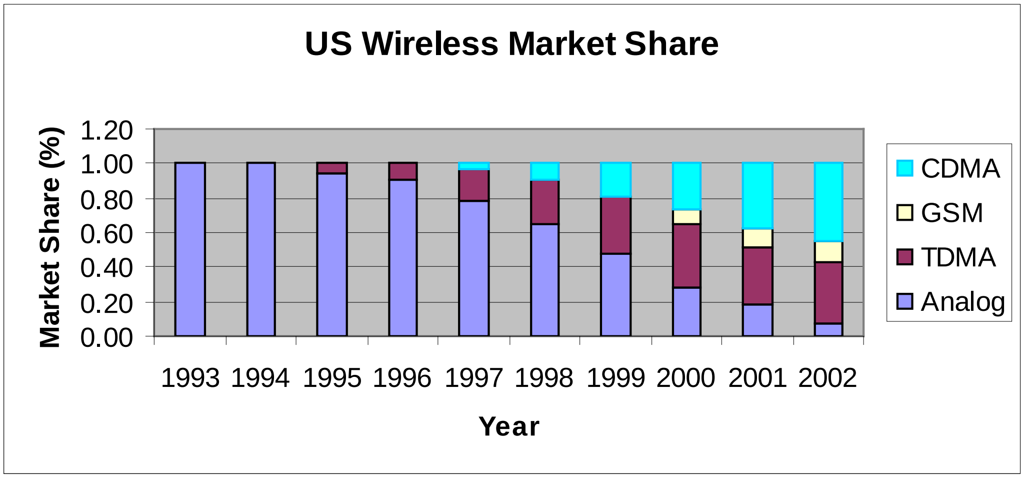


Figure 3.4 US Wireless Market Share

At present, there are three major competing digital standards *CDMA*, *TDMA*, and *GSM*. The US wireless industry permits the coexistence of multiple, competing technologies to give choices to consumers. As addressed before, the analog technology will be removed from the US wireless industry after 2004.

As of March 2004, the US has five nationwide wireless service providers: Cingular-AT&T Wireless, Sprint PCS, Verizon Wireless, T-Mobile, and Nextel. In addition, there are a number of large regional players, including Western Wireless Corp., US Cellular, Dobson Communications Corp., and Alltel.

Each firm uses a different technology or combination of technologies for their current networks, as shown in Table 3.1. Verizon Wireless uses AMPS and *CDMA*; and Cingular and AT&T Wireless use AMPS, *TDMA*, and *GSM*. Sprint Wireless and T-Mobile use *CDMA* and *GSM*, respectively.

Table 3.1 US Wireless Firms' Technologies

<table>
<tr><th></th><th>Verizon</th><th>Cingular-AT&T</th><th>Sprint</th><th>T-Mobile</th><th>Nextel</th></tr>
<tr><td>AMPS</td><td>O</td><td>O</td><td></td><td></td><td rowspan="4">iDEN
(integrated Digital Enhanced Network)</td></tr>
<tr><td>TDMA</td><td></td><td>O</td><td></td><td></td></tr>
<tr><td>GSM</td><td></td><td>O</td><td></td><td>O</td></tr>
<tr><td>CDMA</td><td>O</td><td></td><td>O</td><td></td></tr>
</table>

Cingular-AT&T Wireless:

On February 17, 2004, Cingular announced that it, currently the nation's second largest wireless service provider in the US, had bought AT&T Wireless, the nation's third largest wireless service provider, paying about a 27 percent premium to AT&T Wireless shareholders (CNN news 2004). This combination would make Cingular Wireless the largest US wireless carrier, ahead of Verizon Wireless. Both Cingular and AT&T Wireless networks run on the global system for mobile communications (GSM) standard, the dominant European standard.

Before merger, Cingular, serving about 22.6 million subscribers nationwide as of March 2003 (Budde 2003) , is a joint venture between the domestic wireless divisions of SBC Communications (60%) and BellSouth (40%). The company provides cellular and PCS services in 43 of the nation's top 52 markets and sells services from 15,000 retail locations (Budde 2003).

Verizon Wireless:

Verizon was a leading wireless service provider in the US, providing digital coverage in nearly all US cities, before the merger between Cingular and AT&T Wireless in the early of 2004. Verizon has shown strong growth in 2003 and has cemented its position in terms of subscriber numbers (46 million) and growth (Budde 2003). Verizon Wireless is jointly owned by Verizon

Communications (55%) and Vodafone (45%). Bell Atlantic and Vodafone Airtouch received FCC approval in mid-2000 to form Verizon and have launched their own national service under the name of Verizon Wireless (EMC 2004). Like Sprint PCS, it has launched a CDMA2000 1xRTT network. With the advent of the nation's largest giant competitor, Cingular-AT&T Wireless, Verizon is challenging to overcome this situation for several years in the future.

Sprint PCS:

Sprint PCS operates the largest 100% digital nationwide wireless network serving the majority of the nation's metropolitan areas including more than 4,000 cities (EMC 2004). The company has more than 11,000 cell sites nationwide with CDMA technology. During 2002, the company continued its migration to 3G wireless technology; the first phase of which was implemented in 2001 and completed in 2002. The CDMA2000 1x RTT network was officially launched in August 2002 (Budde 2003). In April 2003, the company began offering photo messaging services as one of the first CDMA operators in the US.

T-Mobile:

T-Mobile (formerly VoiceStream Wireless) is one of the leading wireless service providers in US to use and operate a GSM technology platform as the only US wireless service provider with a national GSM network, although AT&T and Cingular are quickly catching up. This is a strong competitive advantage because customers choose T-Mobile when they travel internationally (especially Europe) and GSM customers from the other countries travel to the USA because of roaming capabilities. The company has established international roaming agreements in over 90 countries worldwide. T-Mobile experienced significant growth over 2001 and 2002 with average revenue per user (ARPU) of $53 (industry average was $45.), and operates in 45 of the top 50 markets in the US (Budde 2003).

Nextel:

Nextel Communications provides fully integrated all-digital wireless services. Nextel uses integrated Digital Enhanced Network (iDEN) technology developed by Motorola (Budde 2003). This technology provides superior sound and transmission quality as well as built-in cloning and fraud protection. The company is one of the operators that is expected to be acquired when the next round of market consolidation occurs in the US wireless market. However, its proprietary technology will potentially make it hard to integrate. No merger partners are expected to emerge until the company announces which (if any) roadmap they will take for 3G wireless services (Budde 2003).

Table 3.2 US Wireless Carriers' Key Statistics (Source: based on company data)

	Verizon	**Cingular-AT&T**	**Sprint PCS**	**T-Mobile**	**Nextel**
Year Established	2000	2000	1998	1996	1987
Headquarters	New York	Atlanta, GA	Kansas	Washington	Virginia
Customers (06/2003)	34.6 Million	44.1 Million	15.3 Million	11.4 Million	11.7 Million
ARPU (6/2003)	$49.22	$51.80	$62.00	$53.00	$69.00
Employees (2002)	227,000	NA	30,000	20,000	15,200
CAPEX (2002)	$4.4 billion	$8.8 billion	$2.7 billion	$5.0 billion	$1.9 billion

* ARPU: Average Revenue Per User

3.2 HISTORICAL EVOLUTION OF WIRELESS TECHNOLOGY

Over the past decade, wireless networks have made giant strides, moving rapidly from first-generation (1G) analog, voice-only communications, to second generation (2G) digital, voice and data communications, and further to third generation (3G) wireless networks as a convergence of wireless and the Internet. Up until now, wireless technologies can be categorized into three generations. This chapter focuses on these three wireless generations.

3.2.1 First Generation Wireless Network

The first generation (1G) networks were developed and installed in the early 1980s (Vriendt 2002). All the 1G systems used analog technology that relied on Frequency Division Multiple Access (FDMA) methods to create multiple radio channels for multiple users (IEC 2003). Analog technology is an electronic transmission technique accomplished by adding signals of varying frequency or amplitude to carrier waves of a given frequency of alternating electromagnetic current (IEC 2003). It is usually represented as a series of sine waves because the modulation of the carrier wave is analogous to the fluctuations of the voice itself.

Figure 3.5 shows the generic transport architecture of a first generation cellular radio network, which includes mobile terminals (MT), base stations (BS) and mobile switching centers (MSC). The MSC maintains all mobile related information and controls each mobile hand-off (Garg 2001). The MSC also performs all of the network management functions, such as call handling and processing, billing and fraud detection (Rapport 1996). The MSC is interconnected with the Public Switch Telephone Network (PSTN) via trunks and a tandem switch.

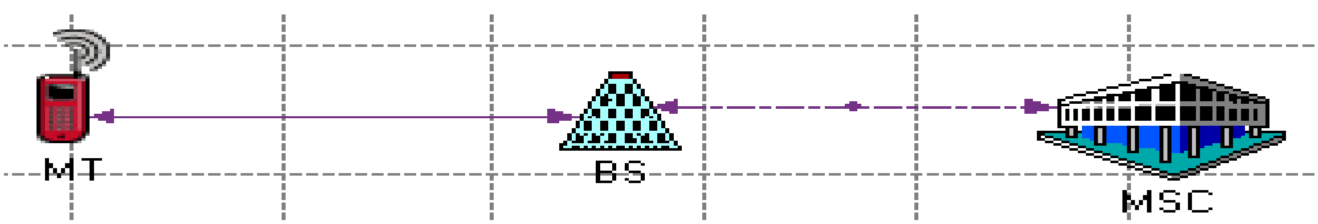


Figure 3.5 First Generation Wireless Network Architecture

The main 'first generation (1G) wireless network' technology standards are AMPS in United States, TACS and NMT in Europe, NTT system in Japan, and others (Dahlman 1998). In the US, Advanced Mobile Phone System (AMPS) (Rapport 1996) as the first generation wireless technology standard was released in 1983 using the 800-MHz to 900-MHz frequency band and the 30-kHz bandwidth with 666 channels for each channel (Garg 2001). It is the first standardized cellular service in the world and is currently the most widely used standard for cellular communications, such as the United States, South America, China, and Australia. Total Access Communication System (TACS) (Rapport 1996) is a mobile telephone standard originally used in Britain for the 900 MHz frequency band.

The TACS is the European version of AMPS. The standard operates on the 900 MHz frequency band, allowing up to 1320 channels using 25 kHz channel spacing (Garg 2001). The TACS are now obsolete in Europe, having been replaced by the more scalable and all-digital Global System for Mobile Communication (GSM) system. Finally, Nordic Mobile Telephony (NMT) (Garg 2001) is the classic cellular standard using 12.5 kHz channel spacing developed by Ericsson and is used in 30 countries around the world.

3.2.2 Second Generation Wireless Network

The second generation (2G) standards were developed and installed in the early 1990s (Vriendt 2002). These systems have shifted to digital technology, primarily using Time Division Multiple Access (TDMA) methods to create multiple access channels for subscribers (IEC 2003). Some 2G systems have deployed Code Division Multiple Access (CDMA) technology, which has further improved system capacity and spectrum efficiency. Digital technology is a way to transmit or store data with a string of 0's and 1's (IEC 2003). Digital technology made its most fundamental technological change in telecommunications (Garg 2001). Using this digital technology, voice signals are digitized and then sent as bits of data over radio waves.

Generally speaking, 2G standards have achieved significant improvements in system capacity, service quality, and information security among other features, compared with 1G system. However, 2G system continues being voice communication focused.

As seen in Figure 3.6, the 2G network architecture has introduced new network architectures different form the 1G network architecture. First, the 2G system reduced the computational burden of MSC and instead introduced the concept of 'Base Station Controller (BSC)' as an advanced call processing mechanism. The BSC is called a radio port control unit, which allows the data interface between the base station and MSC (Garg 2001). Second, the 2G system uses digital voice coding and digital modulation (IEC 2003). Finally, the 2G provides dedicated voice and signaling between MSCs, and between each MSC and PSTN. In contrast to the 1G system which were designed primarily for voice, the 2G has been specifically designed to provide data services (Garg 2001).

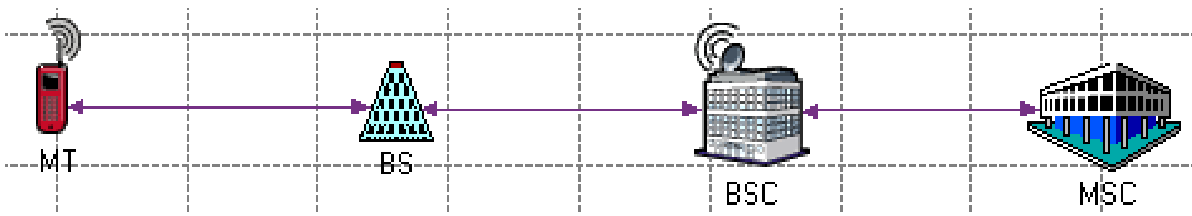


Figure 3.6 The Second Generation Wireless Network

There are several 2G wireless technologies, such as TDMA, GSM, cdmaOne and PDC (Dahlman 1998). 2G systems replaced analog networks (1G) with digital, and allowed data to join the wireless world. One stage before third generation wireless systems comes 2.5G which is a technology that allowed second generation users to get a taste of what 3G would eventually present. 2.5G systems, such as GPRS, EDGE and HSCSD (Rapport 1996; Carsello 1997; Garg 2001; Vriendt 2002; IEC 2003) can be seen as straightforward upgrades of second generation networks, since in most cases, the 2G infrastructures underwent simple software/hardware developments.

Time division multiple access (TDMA) is digital transmission technology that allows a number of users to access a single radio-frequency (RF) channel without interference by allocating unique time slots to each user within each channel (IEC 2003). The current TDMA standard for cellular divides a single channel into six time slots, with each signal using two slots, providing a 3 to 1 gain in capacity over AMPS (Garg 2001).

Global system for mobile communication (GSM) (Rapport 1996) is a globally accepted standard for digital cellular communication. The GSM is the name of a standardization group established in 1982 to create a common European mobile telephone standard that would formulate specifications for a pan-European mobile cellular radio system operating at 900 MHz (Buchannan 1997). Current GSM networks transmit data at 9.6Kbps with a circuit-switched data transmission and allow up to eight users to share a single 200 kHz radio channel by allocating a unique time slot to each user (Garg 2001). The GSM is used in the 900 and 1800 MHz bands all over the world except for North America of 1900MHz band (IEC 2003).

Now GSM carriers are putting a new service which is called General Packet Radio Service (GPRS) (Rapport 1996; Carsello 1997; Garg 2001; IEC 2003), as a 2.5G technology. The GPRS permits packet-switched instead of circuit-switched data transmission at high speed based on the GSM technology (Rapport 1996).

The phase after GPRS is called Enhanced Data Rates for GSM Evolution (EDGE). The EDGE (Garg 2001) is a radio based high-speed mobile data standard that allows data transmission speeds of 384 Kbit/s to be achieved when all eight timeslots are used. The main idea behind EDGE is to squeeze out even higher data rates on the current 200 kHz GSM radio carrier, by changing the type of modulation used, whilst still working with current circuit switches (Rapport 1996).

High Speed Circuit Switched Data (*HSCSD*) (Rapport 1996; Carsello 1997; Garg 2001; IEC 2003) is an enhancement of data services (Circuit Switched Data or CSD) of all current *GSM* networks. It allows you to access non-voice services at 3 times faster, which means subscribers are able to send and receive data from their portable computers at a speed of up to 28.8 kbps; this is currently being upgraded in many networks to rates of and up to 43.2 kbps (Rapport 1996).

The CDMA technology (Rapport 1996; Carsello 1997; Garg 2001; IEC 2003) is a spread-spectrum technology that allows multiple frequencies to be used simultaneously. CDMA technology codes every digital packet it sends with a unique key. CDMA receiver responds only to that key and can pick out and demodulate the associated signal (IEC 2003). The CDMA have claimed bandwidth efficiency of up to 13 times that of TDMA and between 20 to 40 times that of analog transmission.

3.2.3 Third Generation Wireless Network

Nowadays the wireless network architecture is moving to the third generation (*3G*) wireless technologies, which is to provide the high-rate voice and data service (Vriendt 2002). The *3G* system is demanded to provide multi-megabit Internet access with an 'always on' feature and data rates of up to 2.048 Mbps for multimedia services (Rapport 1996).

In the early 1990's, the International Telecommunication Union (ITU) put forth a plan to harmonize ongoing developments of a next-generation wireless network. The initiative was called "IMT-2000," which stands for International Mobile Telecommunications and 2000 refers to both the target for deployment and the approximate frequency at which new wireless devices would operate, 2000MHz.[1]

The 3G wireless system is currently split into two groups: the UMTS group (3GPP) and the cdma2000 group (3GPP2): The Third generation Partnership Project (3GPP) is collaboration between organizational partners (OPs) which study the W-CDMA/TD-SCDMA/EDGE standards and the Third Generation Partnership Project 2 (3GPP2) is collaboration between OPs which examine the cdma2000 standards. (Garg 2001)

The UMTS was developed in 1996 with the sponsorship of the European Telecommunications Standards Institute (ETSI) (Vriendt 2002). In 1998, it was added to the International Mobile Telecommunications-2000 (IMT-2000) standards. It is also known as Wideband CDMA (WCDMA) because it's infrastructure includes several WCDMA standards. WCDMA technology (Rapport 1996; Carsello 1997; Garg 2001; IEC 2003) is an air interface standard in UMTS. The WCDMA technology uses direct spread with a chip rate of 3.84 Mcps and a nominal bandwidth of 5 MHz. The UMTS is an upgrade of GSM/GPRS that has enhanced its spectral efficiency to 6 times.

The network architecture of UMTS is divided into the radio access network (RAN) and the core network (Garg 2001), as shown in Figure 3.7. The RAN contains the User Equipment (UE), which includes the Terminal Equipment (TE) and Mobile Terminal (MT), and the UMTS Terrestrial Radio Access Network (UTRAN), which includes the Node-B and Radio Network

[1] The Evolution of Untethered Communications, p.38.

Controller (RNC) (Rapport 1996). The core network (focused on packet domain) includes two network nodes: the serving GPRS support node (SGSN) and the gateway GPRS support node (GGSN) (Rapport 1996). The SGSN monitors user location and performs security functions and access control. The GGSN contains routing information for packet-switched (PS) attached users and provides inter-working with external PS networks such as the packet data network (PDN).

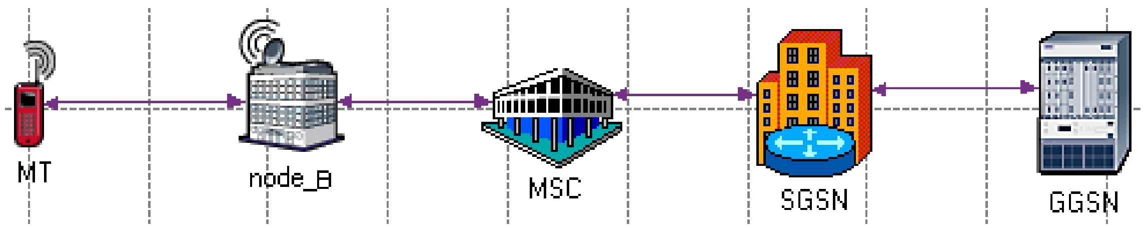


Figure 3.7 The Third Generation Wireless Network (*UMTS*)

The WCDMA technology is network asynchronous, meaning that there is no synchronization between base stations. This implies that no additional source of synchronization is needed (as in cdma2000). In an asynchronous network however, protocols must be carefully designed in order to maintain successful handovers. A handover (or handoff) is a method that takes place when a mobile handset moves from one cell to another so that calls can be transferred to new channels without being interrupted**.**

'cdma2000' (Rapport 1996; Carsello 1997; Garg 2001; IEC 2003) is another wireless standard designed to support 3G services as defined by the ITU and its IMT-2000. 'cdma2000' can support mobile data communications at speeds ranging from 144 kbps to 2 Mbps as WCDMA technology (Garg 2001). The 'cdma2000' uses the same baseline chip rate of 1.2288 Mcps as 'cdmaOne' (Dalal 2002). Each of the individual carriers is modulated with a separate orthogonal code and has an optional overlay mode. This coding distinguishes the 'cdmaOne' and the 'cdma2000' users.

The cdma2000 is a high data rate upgrade of IS-95 (Interim Standard-95, a 2G CDMA standard) that is strictly devoted to the traditional CDMA infrastructure. A 2G mobile carrier adapted to a 3G cdma2000 network has no need of new base stations or channel bandwidth reorganization. The bandwidth of each radio channel remained the same at 1.25 MHz with the difference that up to 3 channels can be used together to provide data speeds in excess of 2.048 Mbps per user (Carsello 1997). Currently the 3GPP2 examines the following standards: CDMA 2000-1xRTT, cdma2000-1xEV, DV, DO and cdma2000-3xRTT. The cdma2000-1xRTT (Radio Transmission Technology) is technically known as G3G-MC-CDMA-1x and supports twice as many users as 2G CDMA with data rates up to 153.6 Kbps (or 614.4 Kbps if all supplemental channels are used).

3.3 TECHNOLOGY MIGRATION PATH

This section presents alternative migration paths and identifies feasible solutions that can support network service providers' network coexistence and migration plans. A simple model is presented to streamline their business and technology strategies indicating how to introduce new network architecture and technologies.

There are several migration scenarios from 2G to 3G for the wireless network operators, but currently the 3G world is split into two alternatives, as seen in Figure 3.8: the cdma2000 which is an evolution of IS-95 ('CDMA-based network migration strategy') and the WCDMA/TD-SCDMA/EDGE whose standards are all improvements of GSM, IS-136 and PDC ('GSM-based network migration strategy'). Still there is not clear which alternative is better towards the 3G.

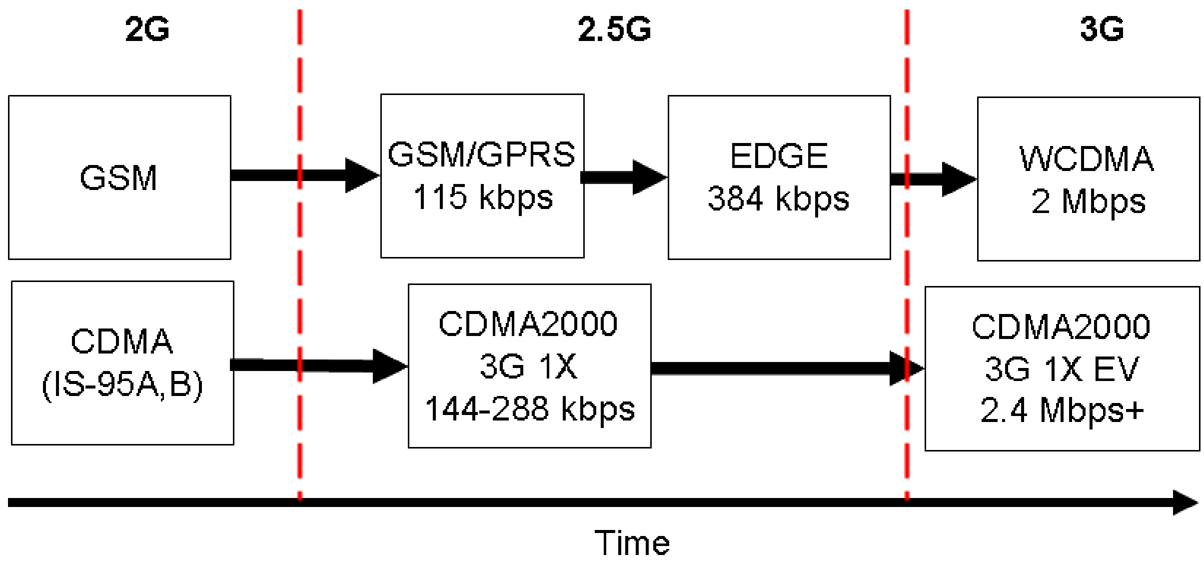


Figure 3.8 Wireless Network Migration Path

3.3.1 GSM-based Network Migration Path

The UMTS does not support hardware reuse in the base station equipment of GSM. The *CDMA* signal requires the use of linear amplifiers and additional filtering in the base station. Operators are forced to install new hardware cabinets adjacent to existing systems. In addition it is not possible to operate in a GSM mode and a UTRAN mode within the same 5 MHz band.

GSM is mainly focused on voice services and offers a useful additional service that is the short message service (SMS). Figure 2.9 shows a simplified architecture of GSM system as specified in the ETSI (TS 101.622). GSM systems consist of three subsystems, the radio subsystem (RSS), the network and switching subsystem (NSS), and the operation subsystem (OSS). RSS is comprised of all the radio specific elements, i.e., the mobile station (MS) and the base station subsystem (BSS) (Garg 2001). NSS is comprised of mobile switching center (*MSC*) and home location register (HLR). OSS is possesses operation and maintenance center (OMC), authentication center (AuC), and Equipment Identity Register (EIR).

As shown in Figure 3.9, when GPRS service is provided in the GSM network, some components are added, like SGSN and GGSN (yellow shaded boxes). Further, a transition from GSM/GPRS to UMTS (3G), access network section (blue shaded boxes) is totally changed or added in the networks.

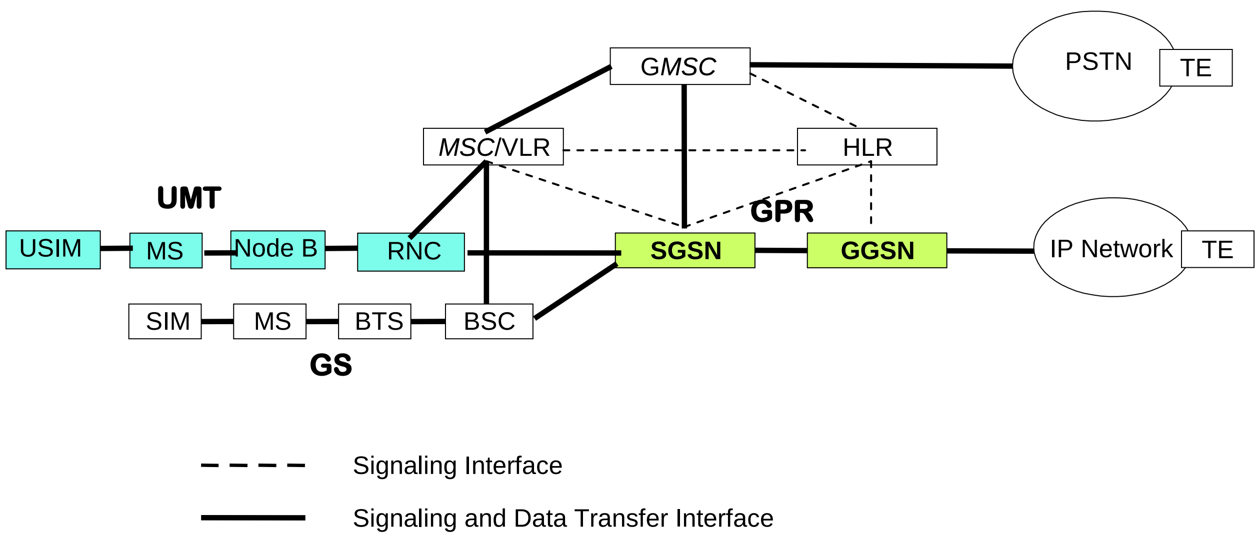


Figure 3.9 GSM-based Network Architecture

Table 3.3 briefly summarized what components are upgraded or replaced in the networks. In case of provisioning GPRS service, it needs simply the upgrades of software nearly without replacement of hardware. While, in case of provisioning UMTS, most of access network facilities are changed because the technology in GSM/GPRS (TDMA-based) is totally different from UMTS's technology (CDMA-based). So, it means a huge of money should be invested for 3G under the GSM-based network architecture.

Table 3.3 Upgrade/New Components in GSM-based Networks

Category	*GSM* to *GSM*/GPRS		*GSM*/GPRS to UMTS	
	HW	SW	HW	SW
Mobile Station (MS) / SIM	Upgrade	Upgrade	New	New
Base Transceiver Station (BTS)	Upgrade	No Change	New	New
Base Station Controller (BSC)	Upgrade	PCU Interface	New	New
Mobile Switching Center (*MSC*)/ Visitor Location Register (VLR)	Upgrade	No Change	No Change	Upgrade
Home Location Register (HLR)	Upgrade	No Change	No Change	No Change
Serving GPRS Support Node (SGSN)	New	New	No Change	Upgrade
Gateway GPRS Support Node (GGSN)	New	New	No Change	No Change

3.3.2 CDMA-based Network Migration Path

Since cdma2000 is the evolution of IS95-based systems, it is the natural 3G evolution of CDMA technology, requiring only minor upgrades to the network and small capital investment (IEC 2003). Because of this, the transition from cdmaOne to cdma2000-1XRTT is relatively easy for operators and transparent for consumers. A service provider can gradually migrate from 'cdmaOne' to cdma2000 at the cdma2000-1XRTT (1.2288 Mcps) rate (Vriendt 2002).

As users migrate to the new standard, network operators can swap out cdma2000-1XRTT and insert a cdma2000-3X radio to increase cell capacity. They also have the choice of using three cdma2000-1XRTTs or converting to a single cdma2000-3XRTT. The cdma2000 reuses the same 9.6 kbps Vocoder from cdmaOne. Figure 3.10 shows the cdma2000-3XRTT network architecture.

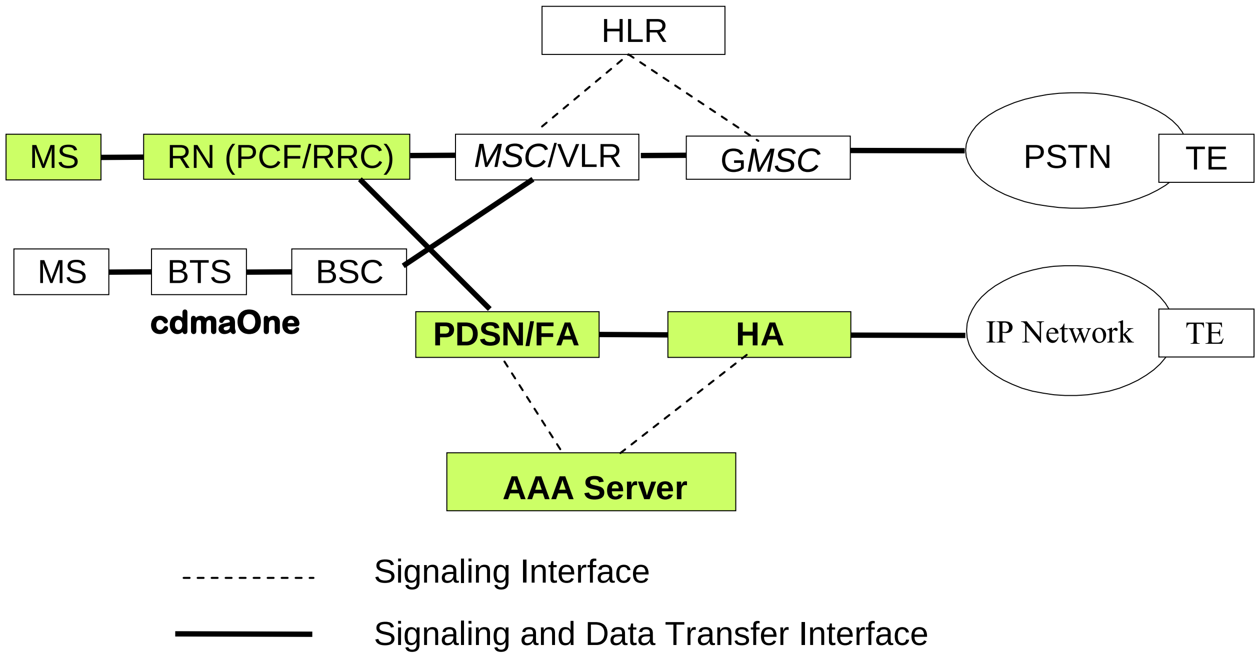


Figure 3.10 CDMA-based Network Architecture

As seen in Table 3.4, the transition from cdmaOne to cdma2000 requires channel card and software upgrades to cdmaOne base stations (older base stations may require some hardware upgrades) and introduction of new handsets. The cdma2000-1XRTT, which is implemented in existing spectrum allocations, delivers approximately twice the voice capacity of cdmaOne, and provides average data rates of 144kbps. The cdma2000-3XRTT standard is used to signify three times 1.25 MHz or approximately 3.75 MHz. The cdma2000-3XRTT multicarrier approach, or wideband cdmaOne, is an important part of the evolution of IS95-based standards.

In short, cdma2000-3XRTT with data rates of up to 2Mbps offers greater capacity than cdma2000-1XRTT. So, unlike a case of UMTS, cdma2000 does not require much investment for the 3G services.

Table 3.4 Upgrade/New Components in CDMA-based Networks

Category	*cdma*One to *cdma2000* 1x		*cdma2000* 1x to *cdma*200 3x	
	HW	SW	HW	SW
Mobile Station (MS)	New	New	No Change	Upgrade
Base Transceiver Station (BTS)	No Change	Upgrade	No Change	Upgrade
Base Station Controller (BSC)	No Change	Upgrade	No Change	Upgrade
Mobile Switching Center (*MSC*)/ Visitor Location Register (VLR)	No Change	Upgrade	No Change	Upgrade
Home Location Register	No Change	No Change	No Change	No Change
Home Agent (HA)/FA	New	New	No Change	No Change
AAA Server	New	New	No Change	No Change
Packet Data Switching Node (PDSN)	New	New	No Change	No Change

3.3 CHARACTERISTICS OF WIRELESS INDUSTRY

The evolution of wireless technologies is being driven by a technology push and a market pull. For example, the development of technology can now push wireless networks to the next generation, while users and service providers want the applications that new technologies could enable (market pull).

Three things have characterized the evolution of wireless technologies: portfolio of innovations, network effect, and substitution effect.

3.4.1 Portfolio of Innovations

One of main characteristics in the evolution of wireless networks is a portfolio of innovations, which means that several types of innovations are mixed or hybrid in each stage of migration. For example, Based on Henderson & Clark' theory (Henderson 1990), the evolution from *GSM* to GPRS is architectural innovation as well as incremental innovation, even though we describe it as incremental innovation in Figure 3.11. This distinction between incremental, modular, architectural, and radical innovations is matters of degree.

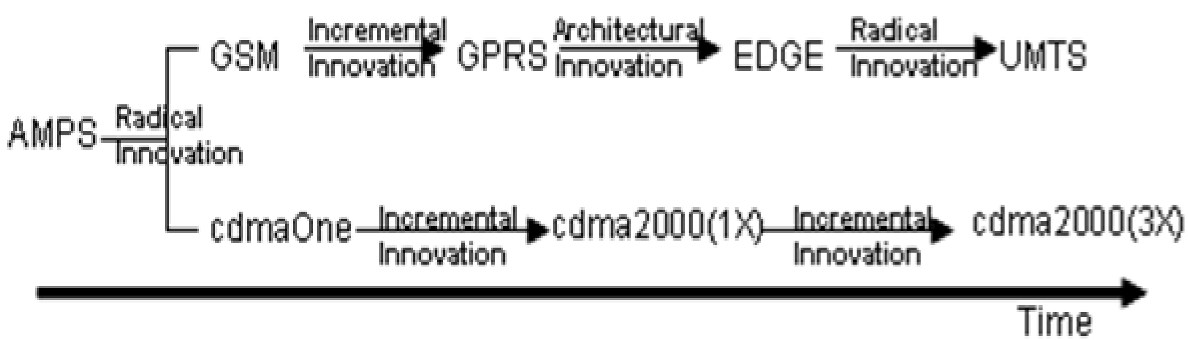


Figure 3.11 Evolutionary Technologies in Wireless Networks

- **Analog to Digital**

The transition from analog to digital technologies, a transition that is occurring at an ever-faster pace, is the change of core concept in network architecture design with a change of linkage between components (BS and *MSC*). Now let's look at what changes are occurred in detail.

First, analog transmission technologies operate on bands of the spectrum with a lower frequency and greater wavelength than subsequent standards. Analog voice signals from the air link are digitized and transformed into 64 kbps pulse code modulated (PCM) bit streams by these *vocoders*.(*radical innovation*) These *vocoders* reside at each BS in the beginning stage. With using the digital cellular compression techniques at the mobile station (MS), it was recognized that it is no longer made economic sense to convert each voice into 64 kbps speech at the BS and use a single DS0 to carry each voice call; therefore, vocoders were moved into *MSC*s.(*architectural innovation*)

Second, digital-to-analog converters (DACs) are one of the most crucial building blocks for telecommunications.(*architectural innovation*) The DACs are one of the key components for wideband radio systems and high speed internet access, like xDSL.

- **GSM to GPRS**

GPRS is essentially based on *GSM* (with the same modulation) and is designed to complement existing services of such circuit-switched cellular phone connections such as SMS (Short Message Service) or cell broadcast. GPRS should improve the peak time capacity of a *GSM* network since it simultaneously transports traffic that was previously sent using CSD (Circuit Switched Data) through the GPRS overlay, and reduces SMS Center and signaling channel loading. In theory, GPRS packet-based service should cost users less than circuit-switched services since communication channels are being used on a shared-use, as 'packets-are-needed' basis rather than dedicated only to one user at a time.

Then, in order to GPRS's data functionality into the existing *GSM* systems, wireless network operators must perform some upgrades to existing equipment without changing any architecture (*incremental innovation*). BTSs undergo a software upgrade, as do *MSC*s, which must be able to handle a new type of data request (*modular innovation*).

- **GPRS to EDGE**

EDGE can provide an evolutionary migration path from GPRS to UMTS by more expeditiously implementing the changes in modulation that are necessary for implementing UMTS later. So, EDGE does not change much of the core network, however, which still uses GPRS/*GSM*. Rather, it concentrates on improving the capacity and efficiency over the air interface by introducing a more advanced coding scheme where every time slot can transport more data. In addition, it adapts this coding to the current conditions, which means that the speed will be higher when the radio reception is good. Implementation of EDGE by network operators has been designed to be simple, with only the addition of one extra EDGE transceiver unit to each cell (*modular innovation*).

With most vendors, it is envisaged that software upgrades to the BSCs and Base Stations can be carried out remotely (*incremental innovation*). The new EDGE capable transceiver can also handle standard *GSM* traffic and automatically switches to EDGE mode when needed. 'EDGE-capable' terminals are also needed, since existing *GSM* terminals do not support new modulation techniques, and need to be upgraded to use EDGE network functionality (*incremental innovation*).

- **Move into 3G**

So, since a move to *3G* needs to change the core design concepts and most of components.(*radical innovation*) For example, *3G* networks require new radio and core network elements. For example, the *3G* radio access network will comprise a RNC (Radio Network Controller) and Node B. A Radio Network Controller (RNC) will replace the Basic Station Controller (BSC). The RNC will include support for connection to legacy systems and provide efficient packet connection with the core network packet devices (SSGN or equivalent). The RNC performs radio network control functions that include call establishment and release, handover, radio resource management, power control, diversity combining and soft handover. Another new piece of network infrastructure for *3G* is Media Gateway (MG) that resides at the boundary between different networks to process end user data such as voice coding and decoding, convert protocols and map quality of service.

3.4.2 Network Effect

The adoption of new technology creates positive or negative effects, which are called '*Network Effect*'. Katz and Shapiro (Shapiro 1999) provide the following definition of *Network Effect*, "a network effect is the increasing utility that a user derives from assumption of a product as the number of other users who consume the same product increases." One example of positive network effects is 'increasing returns' (Arthur 1989) through the usage of a larger distribution network. An example for negative network effects is '*Lock-in Effect*' (Arthur 1989; Liebowitz 1995), which prevents firms from leaving an adopted technology, though the usage of a new technology would be advantageous in the future.

Another phenomenon of network effects is '*Path-Dependency*' mentioned by Arthur (1989). He derives a path dependent process from a random-walk model, where two types of agents have each preference for two types of various technology standards. Agents consume decisions, however, not only depend on their own preference, but also on the overall preference of the other agents.

In the evolution of wireless technologies, we assume that existing technologies grow logistically to their saturation points, and then are replaced by a superior technology that conforms to the market's new requirements. To visualize the impact of new technologies on wireless market shares, this study's parameters are based on a logistic scale, rather than using regression analysis. A logistic scale is useful when little or no data is available, as is the case for new technologies seeking to be market leader.

The first step for visualizing the impacts of new technologies is to estimate the growth rate, Δt_i, and the mid-point of saturation, t_{m_i}, of each technology, based on actual historical data. Using these estimates, Figure 3.12 shows the market value line of each technology. The dots show the actual markets share and the lines are estimated market shares.

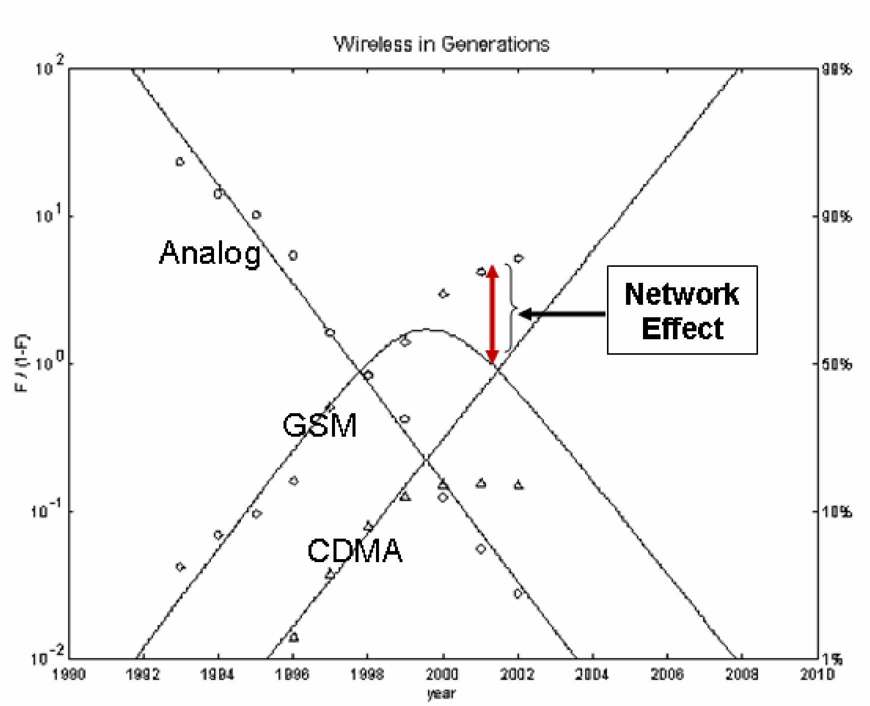


Figure 3.12 Network Effect in Wireless Industry

The large gap between the historical data-based line and the projected line in *GSM* has occurred. This is different from modeling errors because they are already reflected on the projected line. Intuitively, we get some inference as the "network effect" or the "lock-in effect", which means that certain aspects of the network are very difficult to change or replace, and therefore must remain in place.

The network effect in wireless industry is important to explain the emergence and diffusion of wireless technological processes. Its transfer to the domain of wireless technology evolution is not trivial because wireless technologies are much more complex and are developed in many different ways. This may cause various standards to fade out soon, as a result of technological evolution, a phenomenon often called wireless technology generations.

In Europe, for example, *GSM* technology is the universal standard established by the European Telecommunications Standards Institute (ETSI). Conversion from *GSM* to any other technology is not viable because such a huge change is cost prohibitive and network externality is extremely limited.

4.0 TECHNOLOGY DEVELOPMENT

The quantitative methods for valuing real options derived from Black-Scholes option model in financial market (1973). Unlike Black-Scholes model, Cox-Ross-Rubinstein's binomial options model (1979) enabled a more simplified valuation of options in discrete time. Their approach has greatly facilitated the actual valuation of options in practice. They showed that standard option pricing model with risk-neutral valuation can be alternatively derived under risk aversion, and that continuous trading opportunities enabling a riskless hedge or risk neutrality are not really necessary.

There are several studies to value investments with a series of investment outlays that can be switched to alternative states of operation, and particularly to help value strategic inter-project dependencies. Margrabe (1978) developed an equation for the value of an option to exchange one risky asset for another within a stated period. The formula applies to American options, as well as European ones; to puts, as well as calls. One can apply the equation to options that investors create when they enter into certain common financial arrangements. Instead of Margrabe's one asset switching model, Stulz (1982) analyzed options on the maximum or minimum of two risky assets and Johnson (1987) extended Stulz's theory to several risky assets. Further, Carr (1988) explored sequential exchange options, involving an option to acquire a subsequent option to exchange the underlying asset for another risky alternative. These papers opened up the potential to help analyze the generic option to switch among alternative uses, i.e., switch among alternative inputs or outputs.

Another study is in the area of competition and strategy. The sustainable competitive advantages resulting from patents, proprietary technologies, ownership of valuable natural resources, and market power empower companies with valuable options to grow through future profitable investments and to more effectively respond to unexpected adversities or opportunities in a changing technological, competitive, or general business environment.

Roberts and Weitzman (1981) find that in sequential decision making it may be worthwhile to undertake investments with negative NPV when early investment can provide information about the project's future benefits. Baldwin (1982) finds that optimal sequential investment for firms with market power facing irreversible decisions may require a positive premium over NPV to compensate for the loss in value of future opportunities that result from undertaking an investment. Pindyck (1988) analyzed options to choose capacity under product price uncertainty when investment is irreversible. Dixit (1989) considered a firm's entry and exit decisions under uncertainty, showing that in the presence of sunk or costly switching costs it combines Dixit's entry and exit decisions with Pindyck's capacity options for a multinational firm under volatile exchange rates. Kulatilaka and Marks (1988) examined the strategic bargaining value of flexibility in a firm's negotiations with suppliers.

This study develops a theoretical framework for wireless network providers to support their strategic decisions when considering technology choices as they move to the next generation wireless network architecture using the real options approach (ROA). The type of real options is options to switch one technology for another with results. Using well-known techniques (Margrabe 1976, Merton 1973), technology options are assessed for moving to the next generation wireless network architecture and technologiesto determine whether or not to migrate, and, if so, when. For example, in the case of *3G*, wireless carriers have strategic choices for migrating their networks, '*CDMA*-based' or '*GSM*-based', according to their situation. Our model is equivalent to a European option to exchange one risky asset for another (Margrabe 1978) and the extension of the Black-Scholes option model (1973), which implies that the network service provider can exercise at any time, not to wait for until final period like American option.

4.1 DEFINITIONS AND ASSUMPTIONS

Let the option value of technology transition (or 'path') in the revolutionary technology compared with the evolutionary technology be '***H***'. Let ***P*** and ***B*** be the value of two alternatives of network migration by the choice of strategy at time *t*.: One (***P***) is a revolutionary technology change with a larger risk and investment ('aggressive') and the other (***B***) is a stepping-stone technology change with a smaller risk and investment ('conservative').

Also assuming that the level of investment for improving network performance is directly related to their revenues in the market, the key issue in the choice of strategic options is how to quantify a trade-off between the value of network transition and the value of premium in a risk neutral situation. Risk neutrality means comparing one portfolio where an investment is in *stepping-stone architecture* with a premium to the other portfolio where an investment is in the revolutionary architecture with potentially higher value.

4.2 OPTION VALUE VS. PREMIUM

We treat the choice between the two scenarios as a comparison between two alternative technology migration portfolios. Again, let ***P*** correspond to a high level of uncertainty (potentially high value) with a much larger investment cost, and ***B*** correspond to a lower level of uncertainty with a much smaller investment cost. Two scenarios are defined as:

- Revolutionary portfolio $(W_{REV}) = v_P * P$
- Evolutionary portfolio $(W_{EVO}) = v_B * B$

  where v_P and v_B are amounts invested in each scenario.

To compare the two "portfolios", we introduce a quantity $W_{H(P,B)}$ which is defined as:

$$W_{H(P,B)} = v_H * H(P,B)$$

Then, by definition,

$$W_{H(P,B)} = W_{REV} - W_{EVO}$$

Rewritten it as follows.

$$\nu_H H(P,B) = \nu_P P - \nu_B B$$

Using the derivative, it can be described as:

$$\nu_H dH(P,B) = \nu_P dP - \nu_B dB$$

By combining the above two formula, we also can rewrite as:

$$W_H \frac{dH}{H} = W_{REV} \frac{dP}{P} - W_{EVO} \frac{dB}{B} \tag{1}$$

One way to interpret equation (1) is to interpret $H(P,B)$ as the value of the option of investing in the revolutionary technology instead of the evolutionary one and to treat (*B*-*P*) as the value of the premium that should be paid to accomplish higher network performance, under the assumption of risk neutrality. So, $H(P,B)$ should be the maximum premium that should be paid to reduce the uncertainty associated with the evolutionary approach to technology migration. In other words, as long as the actual value of the premium paid for the higher network performance is smaller than $H(P,B)$, it is more advantageous to go for the revolutionary technology.

4.3 TECHNOLOGY TRANSITION VALUE

Now let's consider the time horizon τ to deal with a continuous option, like European-type option which can be exercised at τ. This option is simultaneously a call option on asset one with. Clearly $H(P,B,\tau)$ depends also on the time horizon τ. Remembering that: $W_H = W_{REV} - W_{EVO}$,

$$W_H + W_{EVO} = W_{REV}$$

So, equation (1) can be rewritten as:

$$W_H \frac{dH}{H} = (W_H + W_{EVO}) \frac{dP}{P} - W_{EVO} \frac{dB}{B}$$

$$W_H \left(\frac{dH}{H} - \frac{dP}{P}\right) = W_{EVO} \left(\frac{dP}{P} - \frac{dB}{B}\right)$$

$$\frac{W_{EVO}}{W_H}\left(\frac{dP}{P} - \frac{dB}{B}\right) = \left(\frac{dH}{H} - \frac{dP}{P}\right) \tag{2}$$

$H(B,P,\tau)$ depend on the two stochastic variables ***P*** and ***B*** (i.e. it is a *derivative*) and on the time horizon ***τ***. Using Ito's lemma, the instantaneous rate of change of that derivative $\frac{dH}{H}$ can be written as:

$$\frac{dH}{H} = \beta dt + \gamma dz + \eta dq \tag{3}$$

Where:

$$\beta = \frac{1}{H}\left\{\frac{\partial H}{\partial t} + \mu B\frac{\partial H}{\partial B} + \alpha P\frac{\partial H}{\partial P} + \frac{1}{2}\left\{\delta^2 B^2\frac{\partial^2 H}{\partial B^2} + 2\rho\sigma\delta BP\frac{\partial^2 H}{\partial B\partial P} + \sigma^2 P^2\frac{\partial^2 H}{\partial P^2}\right\}\right\} \tag{3a}$$

$$\gamma = \frac{\sigma P}{H}\frac{\partial H}{\partial P} \tag{3b}$$

$$\eta = \frac{\delta B}{H}\frac{\partial H}{\partial B} \tag{3c}$$

We make the unavoidable assumption that ***P*** and ***B*** follow a geometric Brownian motion with drift (we will have to meditate the validity of that assumption):

$$\frac{dP}{P} = \alpha\, dt + \sigma\, dz \tag{4a}$$

$$\frac{dB}{B} = \mu\, dt + \delta\, dq \tag{4b}$$

The f act t hat hi gh technology h as l ess va riability h ere coul d mean that: $0 < \delta < \sigma$. T o allow the possibility of correlations between the stochasticities of ***B(t)*** and ***P(t)***, we assume that: $\langle dz.dq\rangle = \rho\, dt$, where $-1 \le \rho \le 1$. E quation (2) corresponds i n f act t o t hree e quations. T he coefficients of dt, dq and dz must separately satisfy the equation. Using Equation (4a), (4b), (3), and (2) yields the three equations:

$$\frac{W_{Bt}}{W_H} = \frac{(\beta-\alpha)}{(\alpha-\mu)} = \frac{(\gamma-\sigma)}{\sigma} = -\frac{\eta}{\delta} \tag{5}$$

Together with Equation (3b), (3c), and (5) (more precisely: $\frac{\gamma}{\sigma}+\frac{\eta}{\delta}=1$) leads to:

$$H = P\frac{\partial H}{\partial P} + B\frac{\partial H}{\partial B} \tag{6}$$

One key observation is that EQ.6 can be satisfied by assuming (with $x = \frac{B}{P}$):

$$H(B, P, \tau) = P * h(x, \tau) \qquad (7)$$

Another ke y obs ervation s tems f rom E quation (5) combined w ith E quation (6) and Equation (3a). Namely: $(\beta - \alpha) = (\mu - \alpha)\frac{\eta}{\delta} = \mu \frac{B}{H}\frac{\partial H}{\partial B} - \alpha\left(1 - \frac{P}{H}\frac{\partial H}{\partial P}\right)$ combined w ith E quation (3a), leads to:

$$\frac{1}{2}\left\{\delta^2 B^2 \frac{\partial^2 H}{\partial B^2} + 2\rho\sigma\delta BP \frac{\partial^2 H}{\partial B \partial P} + \sigma^2 P^2 \frac{\partial^2 H}{\partial P^2}\right\} + \frac{\partial H}{\partial t} = 0 \qquad (8)$$

This e quation i s a di fferential e quation f or t he de rivative $H(B, P, \tau)$. U sing $x = \frac{B}{P}$ and Equation (7) and (8) become:

$$\frac{V^2 x^2}{2}\frac{\partial^2 h(x,t)}{\partial x^2} + \frac{\partial h(x,t)}{\partial t} = 0 \qquad (10)$$

$V^2 = \sigma^2 - 2\rho\sigma\delta + \delta^2$ represents the infinitesimal variance of x.[2]

Let $T = \int_t^\tau V^2(s)ds$ be the cumulative uncertainty up until the time horizon $\boldsymbol{\tau}$. By definition of $\boldsymbol{T}$, $dT = -V^2(t)dt$, and Equation (10) can be written:

$$\frac{x^2}{2}\frac{\partial^2 h(x,T)}{\partial x^2} = \frac{\partial h(x,T)}{\partial T} \qquad (10a)$$

Equation (10a) is the Kolmogorov backward equation for the stochastic process:

$$\frac{dx}{x} = d\zeta. \ (\langle d\zeta \rangle = 0 \text{ and } \langle d\zeta^2 \rangle = dT).$$

If on e de fines: $y = \log(x)$, $\frac{dx}{x} = d\zeta$ becomes: $dy = -\frac{dT}{2} + d\zeta$ The ba ckward K olmogorov equation for $\boldsymbol{y}$ is[3]:

$$\frac{1}{2}\frac{\partial^2 h(y,T)}{\partial y^2} - \frac{1}{2}\frac{\partial h(y,T)}{\partial y} = \frac{\partial h(y,T)}{\partial T} \qquad (11)$$

If $f(y) = h(y, T = 0)$, the solution of Equation (11) is[4]:

---

[2] From the definition of x and Ito's lemma: $\frac{dx}{x} = \left[\mu - \alpha - \rho\sigma\delta + \sigma^2\right]dt + \delta dq - \sigma dz$

[3] S. Karlin, R. Taylor: Second Course in Stochastic processes (Academic, New York, 1981), p.220.

$$h(y,T)=\frac{1}{\sqrt{2\pi T}}\int_{-\infty}^{+\infty} f(\xi)e^{-\frac{\left(y-\xi+\frac{T}{2}\right)^2}{2T}}d\xi\ ,$$

This can also be written as (with: $\eta=\frac{\left(\xi-y+\frac{T}{2}\right)}{\sqrt{2T}}$):

$$h(x,T)=\frac{1}{\sqrt{\pi}}\int_{-\infty}^{\infty} f\left(\log(x)-\frac{T}{2}+\eta\sqrt{2T}\right)e^{-\eta^2}d\eta \qquad (12a)$$

What should we use as boundary conditions $f(y)=h(y,T=0)$? If we interpret $h(x,T)$ as the maximum premium that should be paid to invest in high cost technology instead of conservative technology, investing in high technology makes sense only if the premium actually paid (***B-P** or **1-x***) is less than the value of H(*P,B*). In terms of the variable ***x***, this means that $h(x,T)$ must be larger than ***1-x***. This implies that the zero uncertainty limits $h(x,T)=Max[0,1-x]$. Remembering that $y=\log(x)$, this implies that $f(y\le 0)=0$ and

$$f(y>0)=e^y-1=xe^{\eta\sqrt{2T}-\frac{T}{2}}-1$$

Substituting this form for *f(z)* in EQ. 12a eventually yields:

$$h(x,T)=\frac{x}{\sqrt{\pi}}\int_{-\frac{\log(x)+\frac{T}{2}}{\sqrt{2T}}}^{+\infty} e^{-\eta^2}d\eta-\frac{1}{\sqrt{\pi}}\int_{-\frac{\log(x)-\frac{T}{2}}{\sqrt{2T}}}^{+\infty} e^{-\eta^2}d\eta \qquad (13)$$

Which can also be written as (this is our "basic formula"):

$$h(x,T)=x\Phi(d_1(x,T))-\Phi(d_2(x,T)) \qquad (14)$$

With:

$$d_1(x,T)=\frac{1}{\sqrt{2T}}\left[Log(x)+\frac{T}{2}\right] \qquad (15a)$$

$$d_2(x,T)=\frac{1}{\sqrt{2T}}\left[Log(x)-\frac{T}{2}\right] \qquad (15b)$$

[4] Karlin Taylor op.cit., Eq. 5.18, p.217.

$$\Phi(d) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{d} e^{-\eta^2} d\eta \qquad (15c)$$

Notice that $h(x=0,T)=0$. The form of $h(x,T)$ is very similar to Black-Scholes. It differs in at least two important ways: $x=\frac{B}{P}$ is dimensionless and the interpretation of $h(x,T)$.

Remembering that $x=\frac{B}{P}$ and $H(B,P,T)=P\,h(x,T)$, the expression of $H(B,P,T)$ in terms of the value of the evolutionary technology ***P*** and the value of the higher cost technology ***B***, can be deduced from Equation (14):

$$H(B,P,T) = B\cdot\Phi\left(d_1\left(\frac{B}{P},T\right)\right) - P\cdot\Phi\left(d_2\left(\frac{B}{P},T\right)\right) \qquad (16)$$

In Equation (16), $T=(\sigma^2 - 2\rho\sigma\delta + \delta^2)\tau$ is the cumulative uncertainty over the time horizon "τ". When $\sigma >> \delta$, $T \approx \sigma^2\tau$. When the variability is zero, Equation (16) becomes: $H(B,P,0) = Max[0, P-B]$.

In Equation (16), provides an expression for the equivalent of an option $H(B,P,T)$. $H(B,P,T)$ is the extra value of using high technology in risk neutral condition. If the premium associated with high technology, is exactly equal to $H(B,P,T)$, the investor is in a "risk neutral" situation.

5.0 MODELING AND METHODOLOGY

5.1 WIRELESS TECHNOLOGY OPTIONS

As the wireless industry moves toward *3G* technologies, the current coexistence of three major technologies (TDMA, GSM, and CDMA) will most likely evolve into two competing technologies within the *3G* market: *WCDMA* and *cdma2000*. *cdma2000* can be built on top of current *2G CDMA* network, reusing much of the existing infrastructure and cell sites, while *WCDMA* requires more time and money to build out the network.

Figure 5.1 shows the possible technology transition scenarios. The transition from analog (1G) to digital (2G) has three choices: TDMA, GSM, and CDMA. TDMA and CDMA are more popular in the US, while GSM is prevalent in Europe. For more high-speed data services, *2.5G* technologies, *GPRS, EDGE*, and *cdma2000-1XRTT*, have been developed. *2.5G* is always on, provides simultaneous voice and data, and delivers more speed than 2G circuit-switched data connections. *2.5G* offers more bandwidth than *2G* but less than *3G*. Network service providers can implement *2.5G* much less expensively than *3G* because the former uses existing *2G* spectrum and doesn't require a new network infrastructure, although some system upgrades are necessary. So, *2.5G* is a stepping-stone to *3G*.

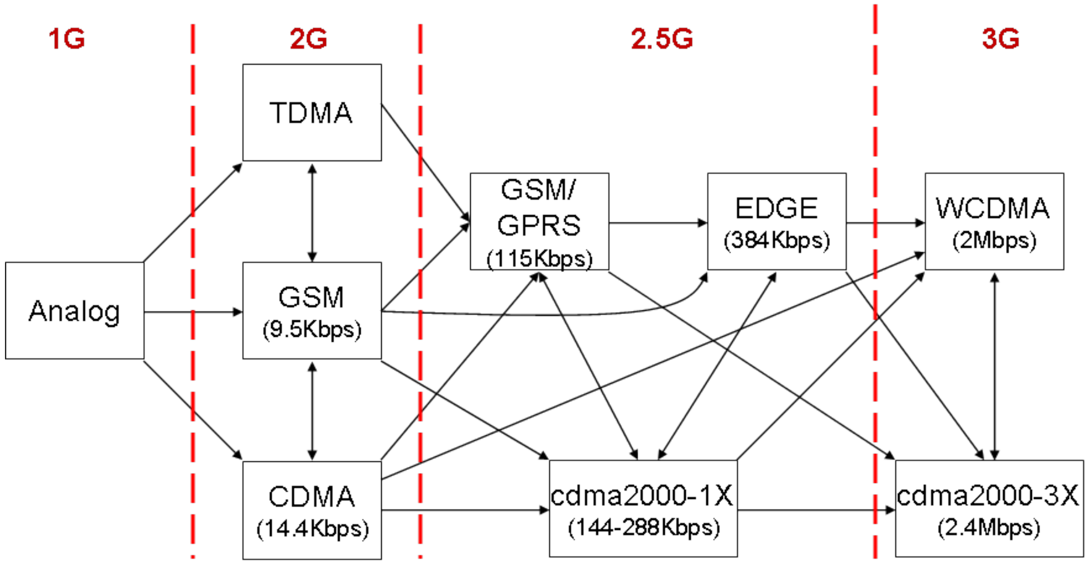


Figure 5.1 Technology Options in Wireless Networks

5.2 MODELING

For a simple illustration, Figure 5.2 shows three types of potential *3G* customers, 1) new customers who have never used wireless phone services, 2) customers who migrate from their current *1G* services, and 3) customers who migrate from their current *2G* services. Continuing with this illustration, four firms are assumed to participate in the wireless market. Firm A is an existing hybrid service provider offering *1G* and *2G* technologies, i.e., Verizon and Cingular-AT&T Wireless. Firm B, also an existing service provider, only offers *2G* services, i.e., Sprint PCS and T-Mobile. Firm C is a new service provider and only offers *3G* services, i.e., *WCDMA* and *cdma2000*. Then, what is a firm's migration strategy in each different environment?

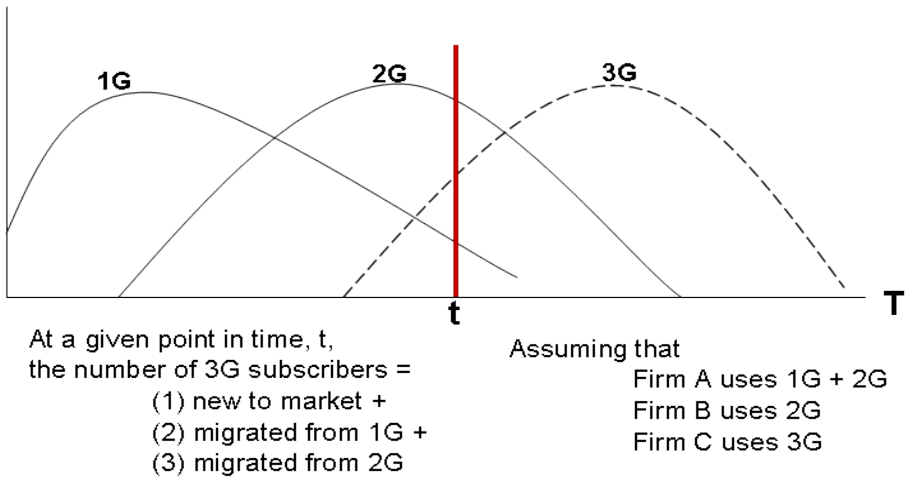


Figure 5.2 Hypothetical Market Structure

Figure 5.3 illustrates the overall design of this study to determine the best technology transition path. Two types of technology migration are identified. First, inter-generational technology migration deals with moving from one generation technology to another, for example, analog-to-*TDMA*, analog-to-*GSM*, and analog-to-*CDMA*. The other type, intra-generational technology migration, i.e., movement within the same generation technology, includes cases such as *TDMA*-to-*GSM*, *TDMA*-*CDMA*, and *GSM*-to-*CDMA*. Based on this structure, a total of sixteen scenarios have been constructed. For each migration scenario, the technology transition value will be calculated using STOM.

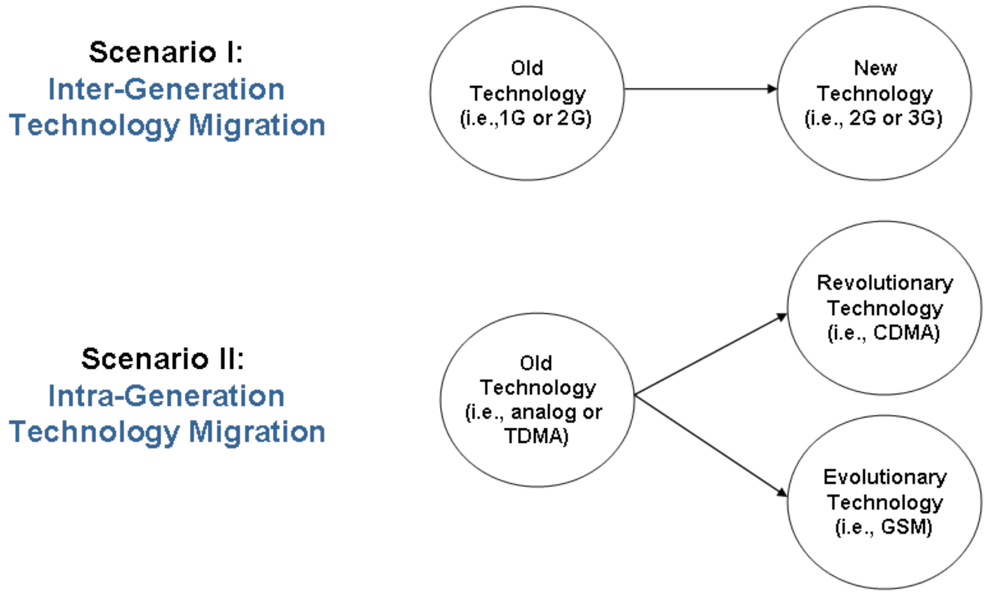


Figure 5.3 Research Design

5.3 SCENARIOS AND PROCEDURE

Several assumptions are applied when we construct these scenarios as follows:

- First, it is impossible to choose technology backward. That is, a firm's always prefers new technologies instead of old technologies.
- Second, a firm's can only one technology when it decides to migrate.
- Third, there is no limitation to choose any technologies. At present, *GSM* is standardized in Europe, but we allow that any technology can be chosen, like US.

Based on theses assumptions, the following is developed as alternative technology migration paths are introduced. The scenario will start with an analog technology based in the year 1992, although it is disappeared within two years. From this base scenario emerge follow-ups.

- Scenario 1: Analog => TDMA => WCDMA
- Scenario 2: Analog => TDMA => cdma2000
- Scenario 3: Analog => TDMA => GSM => WCDMA

- Scenario 4: Analog => TDMA => GSM => cdma2000
- Scenario 5: Analog => TDMA => GSM => CDMA => WCDMA
- Scenario 6: Analog => TDMA => GSM => CDMA => cdma2000
- Scenario 7: Analog => TDMA => CDMA => WCDMA
- Scenario 8: Analog => TDMA => CDMA => cdma2000
- Scenario 9: Analog => GSM => WCDMA
- Scenario 10: Analog => GSM => cdma2000
- Scenario 11: Analog => GSM => CDMA => WCDMA
- Scenario 12: Analog => GSM => CDMA => cdma2000
- Scenario 13: Analog => CDMA => WCDMA
- Scenario 14: Analog => CDMA => cdma2000
- Scenario 15: Analog => WCDMA
- Scenario 16: Analog => cdma2000

Simulations are implemented as the following two steps.

- First, only one step migration path is calculated.
- Second, this calculated one step value is combined to get the value of the whole migration path.

5.4 RESEARCH METHODOLOGIES

5.4.1 Loglet Analysis

Many quantitative studies of technology evolution have adopted a single generation model to simulate the diffusion pattern of demand, such as logistic s-curve (Pry 1971; Marchetti 1980; Meyer 1994). However, this traditional approach only considers the diffusion of the new technology itself, not taking into account new generations, which can replace the one just developed.

Recently a new technique, *Loglet Analysis*, is developed to analyze the complex diffusion process of products or technologies competing in market (Meyer 1999). For example, we can think of different modes of transportation (horses, trains, cars, airplanes, etc.) as competing in the same market. *Loglet Analysis* which is developed by Meyer-Yung-Ausubel (Meyer 1999) at the Rockfeller University refers to the decomposition of growth and diffusion into S-shaped logistic components, roughly analogous to wavelet analysis, popular for signal processing and compression. *Loglet Analysis* could analyze the rise, leveling and fall of competitors substituting for one another. *Loglet Analysis* comprises two models: the first is the component logistic model, in which autonomous systems exhibit logistic growth. The second is the logistic substitution model, which models the effects of competitions within a market.

Component Logistic Model

The component logistic model assumes that a population N(t) of individuals grows or diffuses at an exponential rate α until the approach of a limit or capacity *k* slows the growth, producing the familiar symmetrical S-shaped curve. This model can be expressed mathematically by the following ordinary differential equation (ODE) which specifies the growth rate $\frac{dN(t)}{dt}$ as a nonlinear function of $N(t)$:

$$\frac{dN(t)}{dt} = \alpha N(t)(1 - \frac{N(t)}{k})$$

For values of $N(t) << k$, equation closely resembles exponential growth. As $N(t) \rightarrow k$, the feed back term slows the growth to zero, producing the S-shaped curve. It is easy to solve the logistic ODE to find the function $N(t)$ which satisfies equation:

$$N(t) = \frac{k}{1 + e^{-\alpha t - \beta}}$$

where α is the growth rate; β is the location parameter which shifts the curve in time but does not affect the its shape; and κ is the saturation level at which growth stops.

While κ can be easily seen in a graph, α and β can not. Accordingly, we replace them with two related metrics, the midpoint and growth time. We define the growth time, Δt, as the length of the interval during which growth progresses from 10% to 90% of the limit *k*. Through simple algebra, the growth time is $\Delta t = \frac{\ln(81)}{\alpha}$. We define the midpoint as the time t_m where $N(t_M) = \frac{k}{2}$. Again simple algebra shows $t_m = -\frac{\beta}{\alpha}$, which is also the point of inflection of $N(t)$, the time of most rapid growth, the maximum of $\frac{dN(t)}{dt}$.

The three parameters κ, Δt, and t_m define the parameterization of the logistic model used as the basic building block for *Loglet Analysis*

$$N(t) = \frac{k}{1 + \exp\left[-\frac{\ln(81)}{\Delta t}(t - t_m)\right]}$$

As it turns out, many growth and diffusion processes are actually made up of several sub-processes. Systems (or technologies) with two growth phases follow what we call the *Bi-logistic* model. In this model, growth is the sum of two discrete logistic curve, each of which is a three-parameter logistic:

$$N(t) = N_1(t) + N_2(t),$$

where

$$N_1(t) = \frac{k_1}{1 + \exp\left[-\frac{\ln(81)}{\Delta t_1}(t - t_{m1})\right]}$$

$$N_2(t) = \frac{k_2}{1 + \exp\left[-\frac{\ln(81)}{\Delta t_2}(t - t_{m2})\right]}$$

Naturally, we can examine system-level behavior (i.e., $N(t)$), or we can decompose the model and examine the behavior of the discrete components (either $N_1(t)$ or $N_2(t)$). Wavelets often overlap in time, though this is not a necessary condition. Depending on the order and magnitude of the overlap, the aggregate curve can take on a wide range of appearances.

Now we generalize the bi-logistic model to a *multi*-logistic model, where growth is the sum of *n* simple logistics:

$$N_1(t) = \sum_{i=1}^{n} N\ (t),$$

where

$$N_i(t) = \frac{k_i}{1 + \exp\left[-\frac{\ln(81)}{\Delta t_i}(t - t_{mi}) \right]}$$

Logistic Substitution Model

Now we discuss the logistic substitution model. Technology substitution is a process by which an innovation is replaced partially or completely by another in terms of its market share over a period of time. In this process one technology replaces or substitutes for another with varying degrees of direct one-to-one competition. The replacement of technology may be instantaneous, or it may take considerable time (Marchetti 1995). The advancing technology may seem to be evolutionary or revolutionary depending upon the take-over time period and each successive generation of the technology may have a new niche by creating new customers(Meyer 1999).

The new technology influences the diffusion of both new and old generation technologies (Pry 1971). Some times while one technology is replacing an old technology, a still newer one is replacing it and multiple substitutions take place. In such situations of uncertainty, a study of technology substitution is important for network service providers, whose efforts and huge investments are at stake. Timing of launching of a new technology is also very important, which can be determined with the help of these models.

Two or more than two technologies compete with each other for their market share in the process of evolution substitution. To analyze such cases technological substitution models have been proposed by many researchers, including Floyd (1968), Fisher-Pry (1971) and Blackman (1973). They studied substitution on the basis of measuring the relative market share of old versus new technology competing in market.

The logistic substitution model generates substitution curves, $L_1, L_2, \ldots, L_n$. These curves follow the market share through the three substitution phases: logistic growth, non-logistic saturation, and logistic decline. The first step in generating these curves from the logistic substitution model is to fit a curve to the growth phase of each technology. Reiterating from above, because we are working in the Fisher-Pry transform space, then

$$\ln \frac{L_i}{1 - L_i} = -\frac{\ln 81}{\Delta t_i}(t - t_{mi})$$

is linear, and we can estimate the parameters for such a curve with linear regression. As before, Δt_i is the characteristic growth time for the ith technology, and t_{mi} is the midpoint of the ith technology's period of growth or decline.

Note that for the logistic substitution model, we use a logistic with only two parameters, because the third parameter, saturation level (k) has fixed at 1, or 100%. Without the introduction of a new technology, the last technology in the growth phase would grow to a 100% market share. If a new technology is introduced, its growth must come at the cost (primarily) of the leading technology, causing it to saturate and decline.

The growth and decline phases can be represented by logistic curves, but this is not the case for the saturation phase. Because only one technology(L_s) can be saturating at a time, its market share can be calculated by subtracting the sum of the shares of all the other technologies-which must be known, since they must be either growing or declining-from unity (100%):

$$L_i = \sum_{i \neq} L_j$$

How do we know when each phase begins or ends? If

$$y_i(t) = \ln \frac{L_i(t)}{1 - L_i(t)} \ ,$$

then the termination of the saturation phase comes at time t at which

$$\frac{y_i''(t)}{y_i'} \text{ is at a minimum}$$

When the saturation phase for a technology ends, it proceeds directly into its decline phase, and the saturation phase for the next technology immediately commences. The two parameters for the logistic decline phase of the curve are given by:

$$\Delta t_i = \frac{\ln(81)}{y_i'(t)}$$

$$t_{mi} = \log \frac{(y_i(t) - \frac{\ln(81)}{\Delta t} t)}{\frac{\ln(81)}{\Delta t}}$$

The logistic substitution model describes the fraction of the niche or market share of the competitors. The life cycle of a competitor can be partitioned into three distinct phases: growth, saturation and decline (Grubler 1990). The growth and decline phases represent logistic growth processes, which as we will see, influences the saturation phase. The assumptions behind the logistic substitution model, as developed by Nakicenovic and Marchetti (Nakicenovic 1979; Marchetti 1995) are:

- New technologies enter the market and grow at logistic rates.
- Only one technology saturates the market at any given time.
- A technology in saturation follows a non-logistic path that connects the period of growth to its subsequent period of decline.
- Declining technologies fade away steadily at logistic rates uninfluenced by competition by new technologies.

The first assumption implies that growth can be modeled with an S-shaped logistic. The fourth also implies that the decline phase can also be modeled with a logistic with a negative Δt. The second and third allows us to determine saturation behavior by competition from emerging technologies.

Implementation of Loglet Analysis

Loglet Analysis condenses the logistic substitution model into two steps. First, it Fisher-Pry transforms all of the data to assist in the identification of the growth (and decline) phases. Second, it asks you to give either a time window for the growth (or decline) phase or a set of parameters for each technology. Using this input, the logistic substitution engine fits a curve to the growth (or decline) phase of each technology, determines the saturation point based on the criterion in equation, and plots the substitution curves. *Loglet Analysis* can accommodate an arbitrary amount of data sets, so users can easily add one or more hypothetical competitors and envision several different scenarios for the emerging markets.

5.4.2 Real Options Approach

This dissertation introduces the concept of real options as a special type of 'switch options'. Various forms of wireless technology choices of carriers are discussed as technology options, including 1G, 2G, and 3G wireless technologies. Although many of technology choices contain technology options, they have not been formally analyzed in real option research. This dissertation not only provides valuation theory for these technology choices, but also analyzes the strategic decisions of choosing among them.

The model which is developed in Chapter 4 consists of two parts; one part is the technology transition option value (TTOV) and the other part is the premium (opportunity costs). The decision for moving to new technology from old technology is that, if the option value of technology transition (***H***) is bigger or equal to premium value (***P-B***), a firm should consider migrating.

$$H(B,P,t) \geq P - B \quad \Leftrightarrow \quad \frac{H(B,P,T)}{B} \geq \frac{P}{B} - 1$$

where $H(B, P, t)$ is technology transition option value

$(P\text{-}B)$ is premium value.

The most desirable time to migrate when STOM reaches its peak value; however, a firm generally may consider other important factors, such as nation or industry's economic, political, and social situations.

6.0 RESULTS AND ANALYSIS

This chapter discusses and analyzes the results from the model including model validation. It is desirable to use all relevant data concerning technological development problems, but such data is generally unavailable in the market. So, the scope of this study is limited to only current market share data for the competing technologies in each generation. However, despite the data limitation, numerous experiments have been conducted by managing the model's parameters, and the results were used to explain current situations and give some clues to establish effective strategies. Although this study is purposely limited in scope, it can be expanded by considering other scenarios under different assumptions. The aim of this case study is to provide insight on the transition strategy of wireless service providers towards the next generation wireless network technologies.

6.1 MODEL VALIDATION

This section shows the validation of *Loglet Analysis* model as a tool to forecast future wireless market. There are many statistical tools for model validation, but they can be categorized in two types: one is numerical methods, such as the R^2 statistic, and the other is graphical methods. Numerical methods for model validation are useful, but usually to a lesser degree than graphical methods. Graphical methods have an advantage over numerical methods for model validation because they readily illustrate a broad range of complex aspects of the relationship between the model and the data. So, this dissertation study uses the graphical residual analysis, which is that different types of plots of the residuals from a fitted model provide information on the adequacy of different aspects of the model.

The Loglet model is nonlinear, as it contains an exponential term. Although there are no direct methods for estimating the parameters for nonlinear models, we can use iterative methods for this purpose. Such methods minimize some function of the residuals.

The standard method for estimating model parameters is the method of least-squares, where the sum of the squares of the residuals is minimized. In our notation, our goal is to vary $\boldsymbol{P}$ such that $X^2 - \sum r_i^2$ is minimized.

Thus we must set $\boldsymbol{P_0}$, which holds initial values for $\boldsymbol{P}$, and iteratively adjust its entries until X^2 has sufficiently converged to a minimum. Note that we do not have to adjust all the entries of $\boldsymbol{P_0}$; there may be reason to hold any one of the entries constant. For example, there may be physical constraints to the growth (the size of the Petri-dish limits the population of a bacteria culture), or time constraints on the midpoint or growth time.

- **Least-square Method and Residuals**

The least-squares method assumes errors are randomly and normally distributed; however, it is often hard to predetermine the error distribution of historical data sets. Least-squares can still be used, but the parameter value estimates are no longer guaranteed to be correct. In fact, on data sets with outliers, or systematic errors, least-squares regression produces poor results. For example, least-squares parameter estimates for logistic functions can overestimate the saturation value (k), because it is less sensitive to error for smaller data values. Thus, when using Loglet Lab, it is usually a good idea to try a second fit with the saturation held at, say, 90% of the final value from the first fit and compare the new fit as well as the new residuals. In addition, we have found that using the Fisher-Pry transform to corroborate the fit can help produce more useful results.

Residuals are the error, or difference, between the model and the observed data. The residual vector $\boldsymbol{R}=\{r_1, \ldots, r_n\}$ is defined by

$$r_i = d_i - N(t, P).$$

Residuals can also be calculated as percentage error:

$$r_i = \frac{(d_i - N(t,P))}{N(t,P)} \times 100.$$

It is crucial to examine the residuals after a fit. When a fit is good, the residuals are non-uniformly distributed around the zero axis; that is, they appear to be random in magnitude and sign. A substantial or systematic deviation from the zero axis indicates some phenomenon is not being modeled or fitted correctly. An iterative process of fitting Loglets to a data set and then examining the residuals is a good way to proceed, unless the errors in the data and shown in the residuals are known to come from other sources (e.g., a recession).

Figure 6.1 shows the actual US wireless subscriber data and the fitted line from 1985 until 2002. From left to right on the chart, the first curve indicates Analog subscribers, the second is *CDMA* subscribers, and the third represents *TDMA*/*GSM* subscribers.

Below, the residual scatter plot of the residuals from a line fit to the actual data does not indicate any problems with the model. The reference line at zero emphasizes that the residuals are split about 50-50 between positive and negative. There are no systematic patterns apparent in these plots.

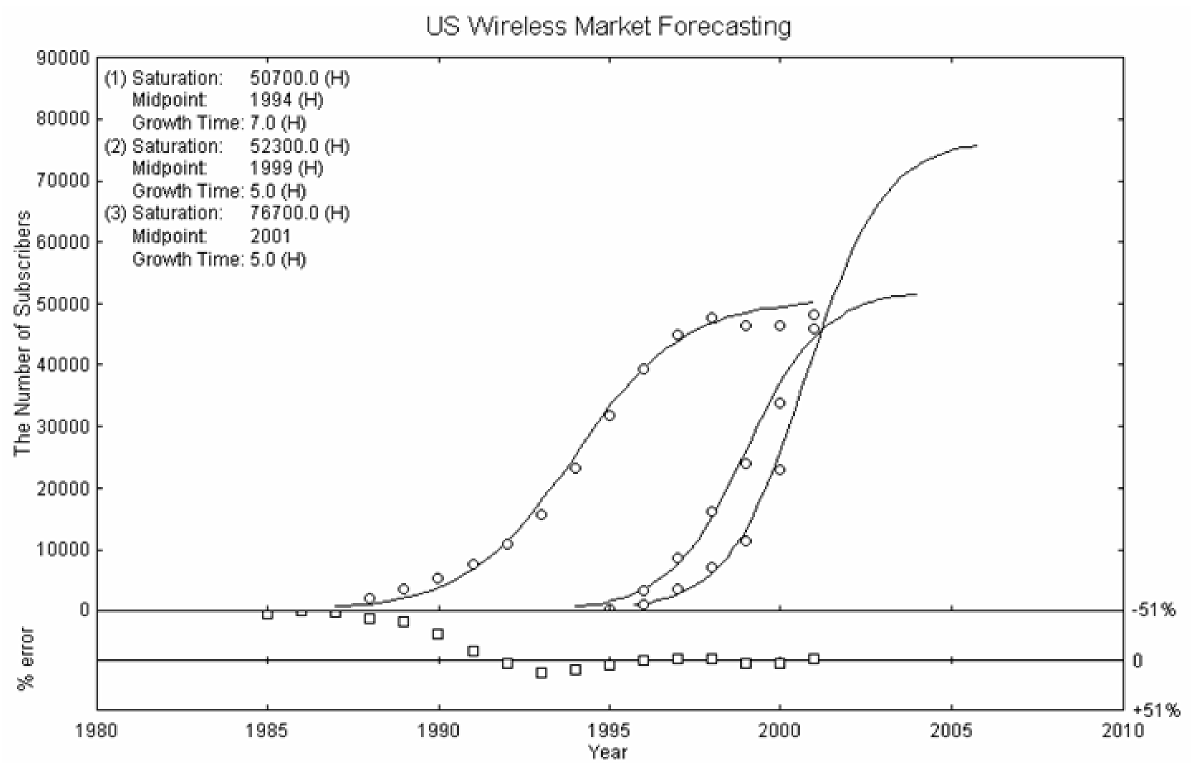


Figure 6.1 Fitting Lines and Graphical Residuals

- **Confidence Intervals on the Estimated Parameters: The Bootstrap**

An important question to ask of a least-squares fit is ``How accurate are the estimated parameters for the data?" In classical statistics, we are accustomed to have at our disposal not only single-valued estimates of a goodness of fit, but confidence intervals (CI) within which the true value is expected to lie. To ascertain the errors on the estimated parameters with classical statistics, the errors of the underlying data must be known. For example, if we know that the measurement errors for a particular dataset are normally distributed (far the most common assumption), with a known variance, we can estimate the error of the parameters.

However, for historical datasets, it is often impossible to know the distribution and variance of the errors in the data, and thus impossible to estimate the error in the fit. However, a relatively new statistical technique allows estimation of the errors in the parameters using a Montecarlo Algorithm.

The Bootstrap Method (Tibshirani 1993) uses the residuals randomly picked from the least squares fit to generate synthetic data sets, which are then fit using the same least squares algorithm as used on the actual data. We synthesize, say, 1000 data sets and fit a curve to each set, giving us 1000 sets of parameters. By the Central Limit Theorem, we assume the sample mean of the bootstrapped parameter estimates are normally distributed. From these sets we can proceed to estimate confidence intervals for the parameters. From the confidence intervals of a parameter, we can form a confidence *region* which contains the set of all curves corresponding to all values of each parameter.

We first estimate the loglet parameters $\boldsymbol{P}$ using the least-squares algorithm described above and calculate the residuals $\boldsymbol{R}$. We then create n_{boot} synthetic data sets adding $\boldsymbol{R_{synth\ i}}$, a vector containing n residuals chosen at random (with replacement) from $\boldsymbol{R}$:

$$D_{synth\ i} = N(t, P) + R_{synth\ i}$$

We then estimate the bootstrap parameters $\boldsymbol{P_{boot\ i}}$ from $\boldsymbol{D_{synth\ i}}$. In Loglet Lab, the default number of synthetic datasets for the simulation is 1000, but this number can be varied depending on the number of data points. Larger datasets may require more runs for accurate statistics. The results are stored in a three-dimensional matrix $\boldsymbol{P_{boot}}$.

The distribution of the parameters in $\boldsymbol{P_{boot}}$ is assumed to be normal, and thus the 95%C.I. can be estimated by calculating the mean μ and standard deviation σ of each parameter in $\boldsymbol{P_{boot}}$, and using the formula:

$$95\%CI : \mu \pm \sigma$$

When performing a Bootstrap analysis in *Loglet Analysis*, keep in mind the importance of first examining the residuals for outliers or other suspect data points. Reasons may exist to mask these outliers before performing the bootstrap, as a large residual value can unduly leverage a least-squares fitting algorithm. If the data are very noisy or contain many outliers, the least-squares algorithm might not converge during one of the many Bootstrap runs, producing unrealistic CI.

Figures 6.2 (varying saturation level), 6.3 (varying midpoint), and 6.4 (varying growth time) show a Bootstrap analysis of the logistic growth of US wireless market as determined by 1,000 runs of the Bootstrap algorithm described above, along with the mean and 95% confidence interval (CI) marked by the solid lines. To show how the completeness of a data set influences the confidence interval, Figure 6.2, 6.3, and 6.4 fit a single logistic to the same data, but the upper and lower solid lines show the 95% CI varying saturation point, midpoint, and growth time, respectively in analog technology. See other technologies CI (95% or 68%) more in detail in appendix.

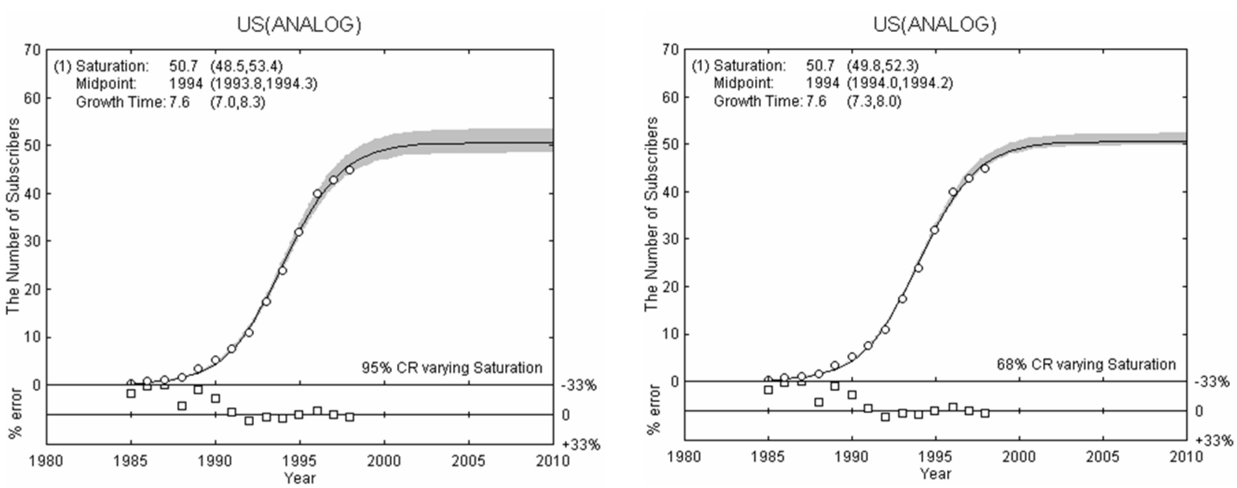


Figure 6.2 95% and 68% CI of US Analog – varying saturation

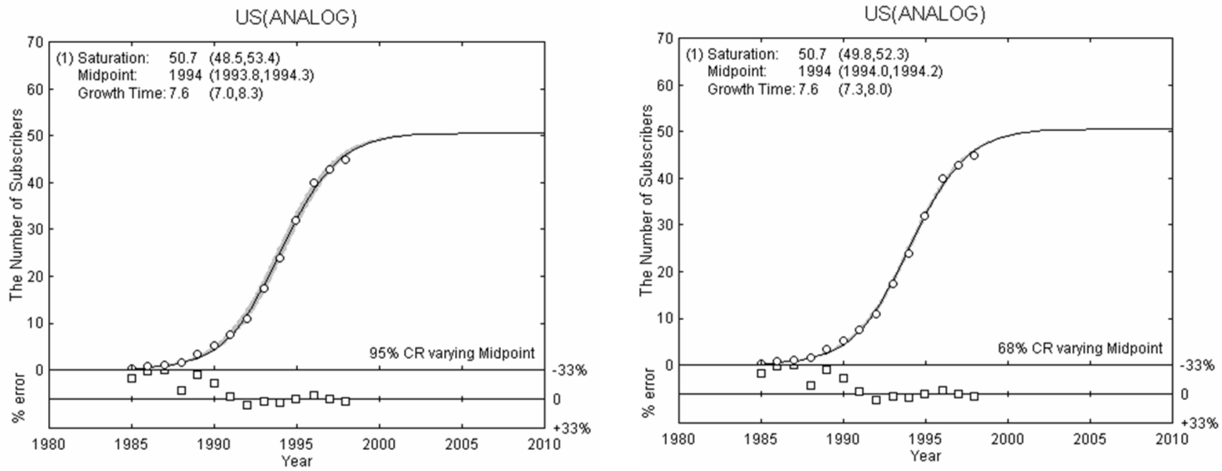


Figure 6.3 95% and 68% CI of US Analog – varying midpoint

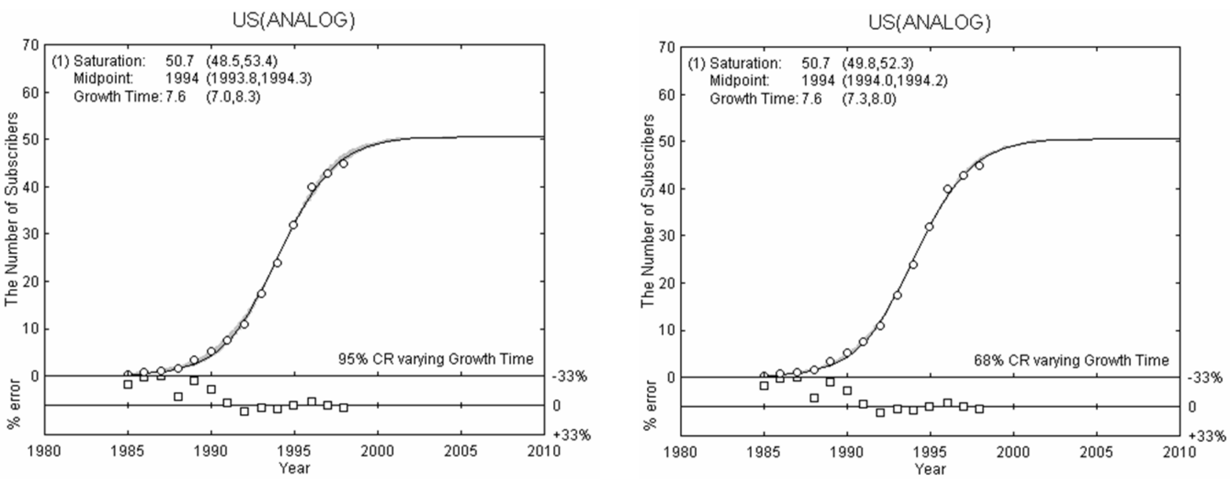


Figure 6.4 95% and 68% CI of US Analog market – varying growth time

6.2 MARKET FORECASTING

6.2.1 Existing Wireless Technologies

Based on 1985-2002 historical data and using *Loglet* software, Table 6.1 shows the three important parameters to forecast the 2003-2010 analysis periods. In the absence of data for WCDMA and cdma2000 in 3G, the total market of 3G is estimated and then simply divided according to the current market share for CDMA and GSM because the 3G market will most likely evolve from GSM to WCDMA and from CDMA to cdma2000.

Table 6.1 Estimation of Loglet Parameters for each technology

Technology	Saturation * (Millions)	Midpoint ** (Year)	Growth Time *** (years)
Analog	50,700	1994	7.6
TDMA	52,300	1999	5.0
GSM	26,000	2001	7.1
CDMA	77,900	2001	4.7

Notes: * Maximum value of this logistic and ratio to prior saturation (in parentheses)

** The point of inflection of the curve

*** Time in which the logistic goes from 10% to 90% of its expected saturation level

Figure 6.5 incorporates the US market forecast through 2010 for each individual technology with a single logistic, with the parameter values estimated using the least squares algorithm. Despite the upward trend of the historical data, Analog technology is not a viable technology for the future. The *Loglet Analysis* is unable to forecast a downward trend for an individual technology; therefore the declining Analog forecast will be addressed later when the study assesses the value of each type of service.

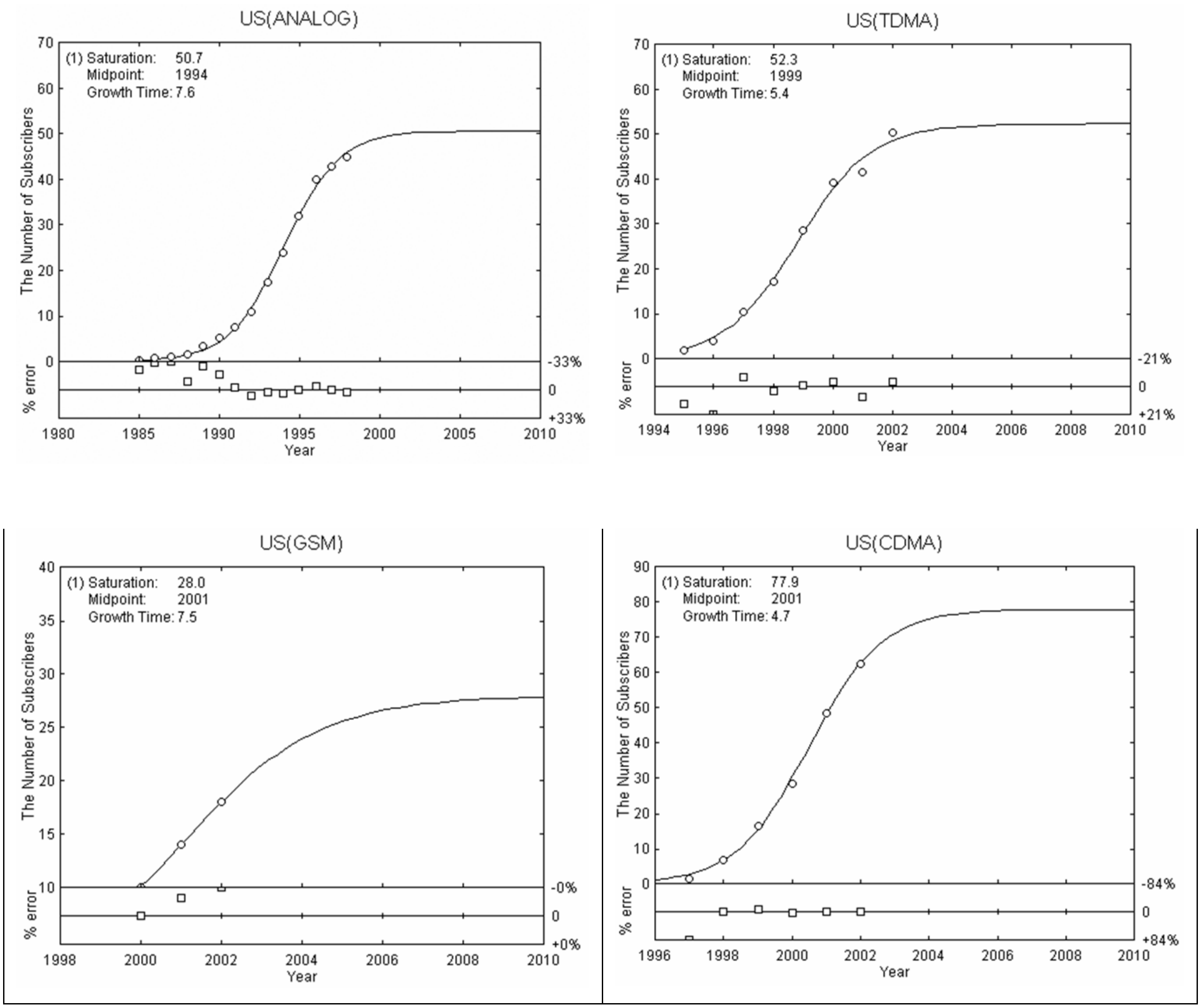


Figure 6.5 Forecasting US Wireless Technologies

Figure 6.6 shows the results of the world wireless market forecast through 2010 for each individual technology.

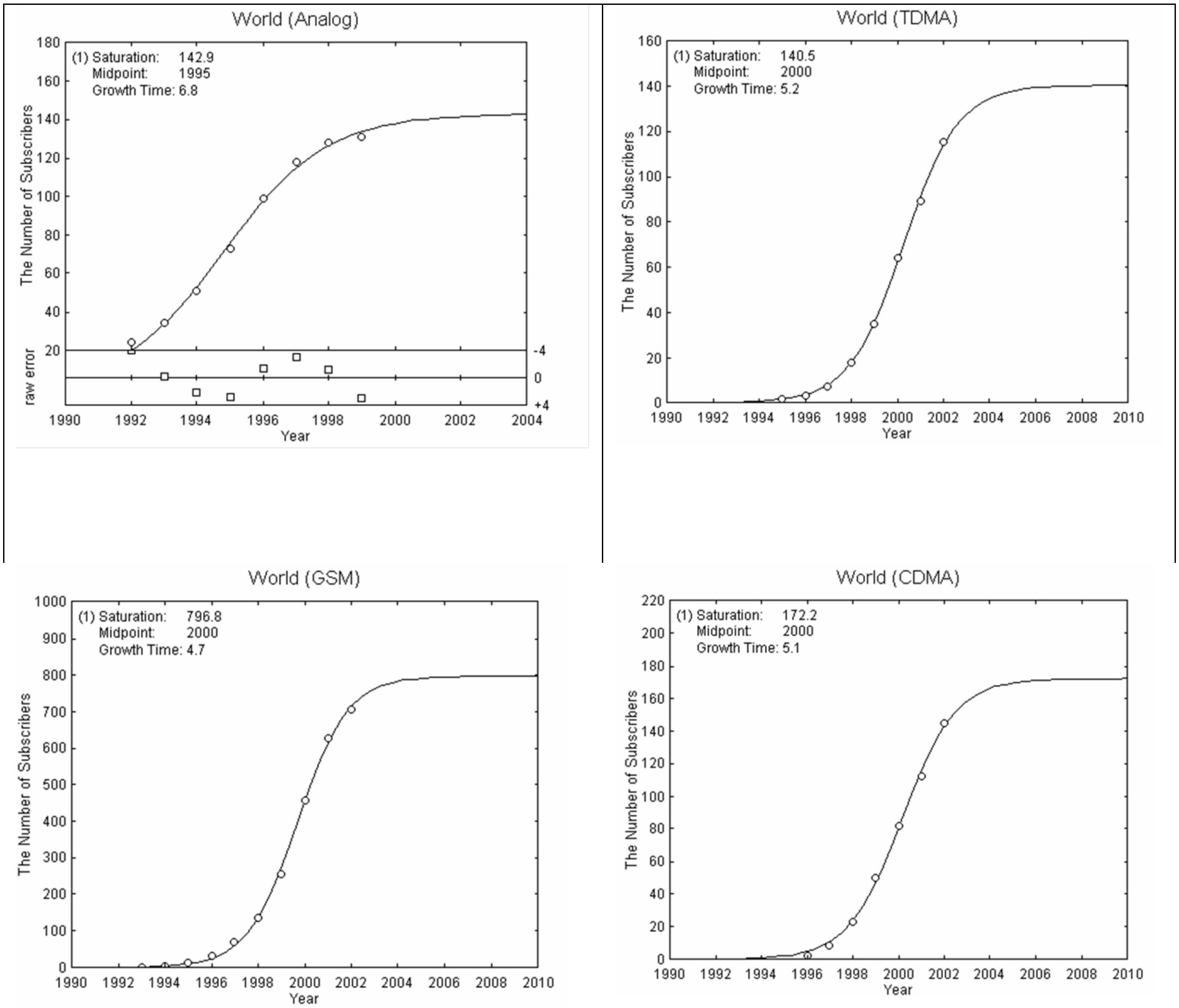


Figure 6.6 Forecasting World Wireless Technologies

6.2.2 3G Technologies

Using world wireless market data, Figure 6.6 shows the substitution of *2G* for *3G* technology (i.e., *WCDMA* and *cdma2000*) in the high-speed multimedia services market. Market share is based on the number of subscribers, and the substitution effect is felt upon introduction of the new technologies.

Projected growth rates and mid-point saturation values for the *3G* technologies are based on the value estimations for *GSM* and *CDMA* technologies (See Figure 6.7). In the base case, using a growth rate of 7% and a mid-point of saturation in 7 years, *3G* technology realizes a 50% market share in 2010.

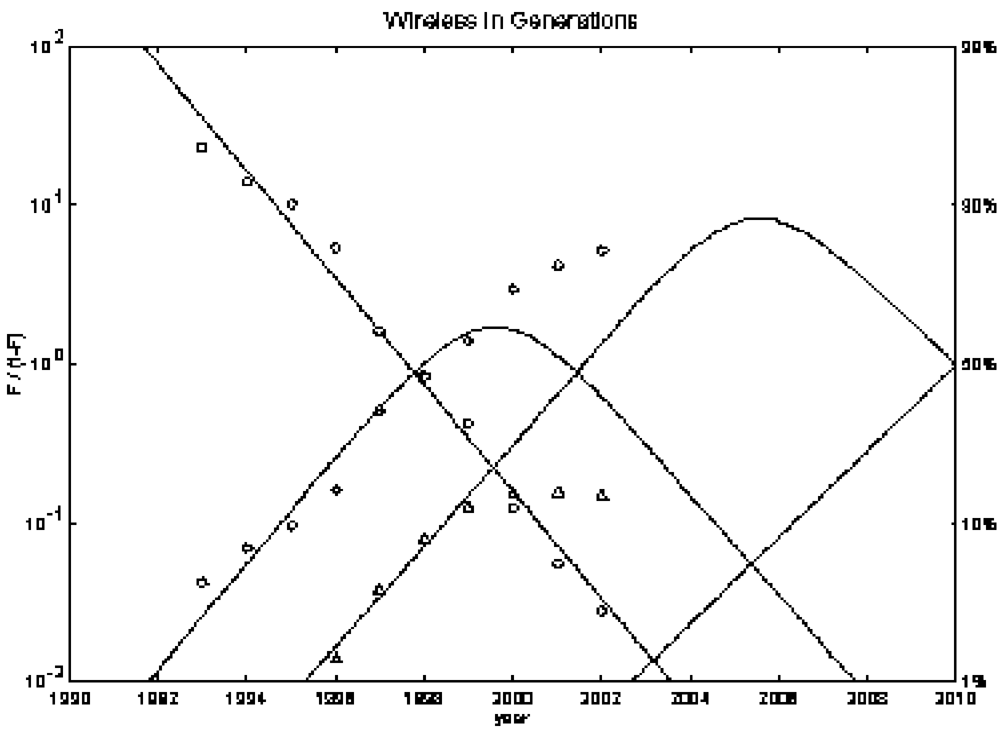


Figure 6.7 3G Wireless Market Forecasting

3G markets are assumed that WCDMA and cdma2000 have the same market share (i.e., WCDMA: 50%, cdma2000: 50%) as a basic scenario. And then sensitivity analysis will be implemented by assuming two possibilities: one is WCDMA market dominance (i.e., WCDMA: 90%, cdma2000: 10%) and the other is cdma2000 market dominance (i.e., WCDMA: 10%, cdma2000: 90%).

6.3 REAL OPTIONS RESULTS

6.3.1 Case of USA

- **Inter-Generational Transition (1G=>2G)**

The first scenario is to move from Analog to *TDMA* network architecture in the US. Figure 6.8 shows that the premium value begins as positive and gradually decreases, becoming negative after 2000. While option value is negative at the initial stage, it gradually increases and becomes positive in 2000. Net option value is negative for a long time, but becomes positive after 2000. Like the world market, analog technology in the US has been popular for a long time. The only difference between the two markets relates to timing. Compared to the rest of the world, analog technology in the US has maintained a dominant position for about two years more, so the transition period to *TDMA* will be longer.

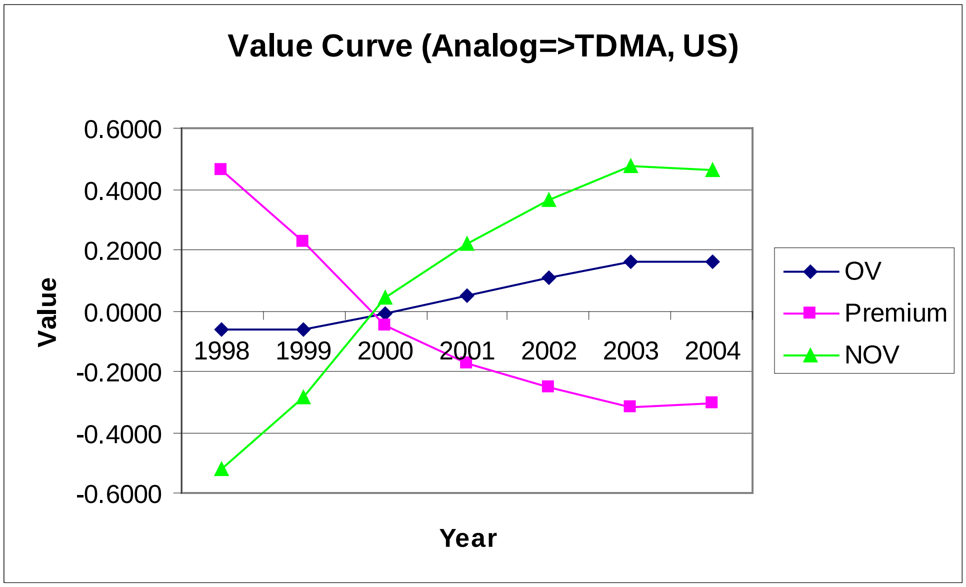


Figure 6.8 Analog-TDMA Scenario (US)

Figure 6.9 shows the results of moving from Analog to *GSM* network technologies. In this case, the result is similar to the previous case. The premium value decreases continuously, but the option value increases gradually because of the high growth rate of *GSM* technology, resulting in a negative net option value until 2001, when it becomes positive. So, the transition from *1G* to *2G* is desirable starting in 2001 or later.

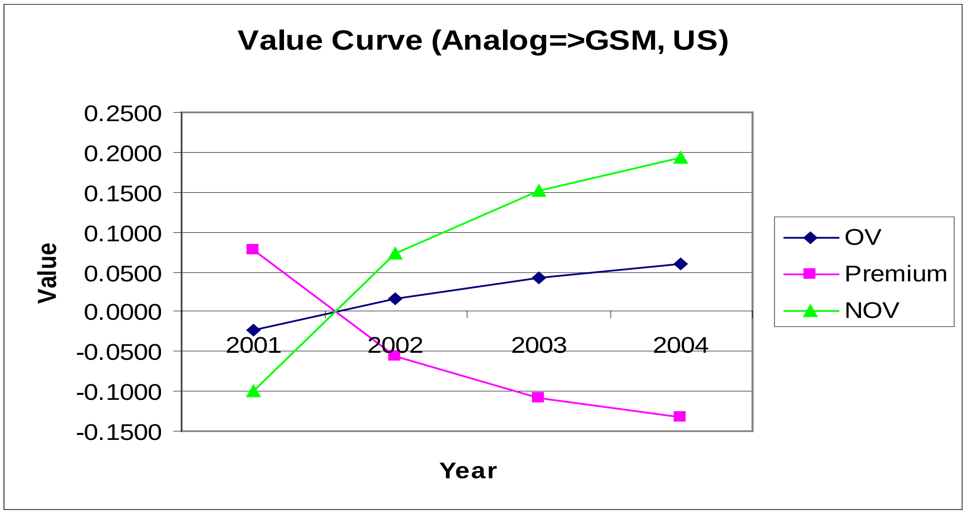


Figure 6.9 Analog-GSM Scenario (US)

Moving from Analog to *CDMA* network technology is totally different results with world market. Unlike world market, the transition is desirable starting in 2000 or later (Figure 6.10). *CDMA* is rapidly growing in the US market, so the transition is suggested as soon as possible. However, *CDMA* in the world market is not strong compared to *GSM*. This is why different results are coming.

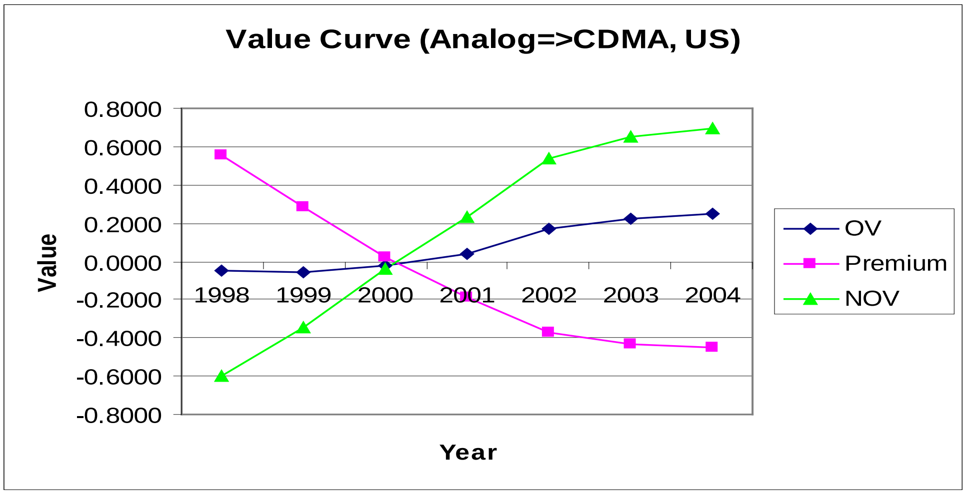


Figure 6.10 Analog-CDMA Scenario (US)

- **Intra-Generational Technology Transition (2G=>2G)**

The next scenario (Figure 6.11) displays the value curve when moving from *TDMA* to *GSM* network technology. This analysis shows that the transition is undesirable because the premium value is positive continuously and the option value is always negative. Since the net option value fluctuates in the level of negative over time, transition should be delayed or never. Since *TDMA* and *GSM* is similar technology and don't need to invest in this transition. However, in reality, operators prefers to transit from *TDMA* to *GSM* as a stepping stone evolution, like AT&T Wireless.

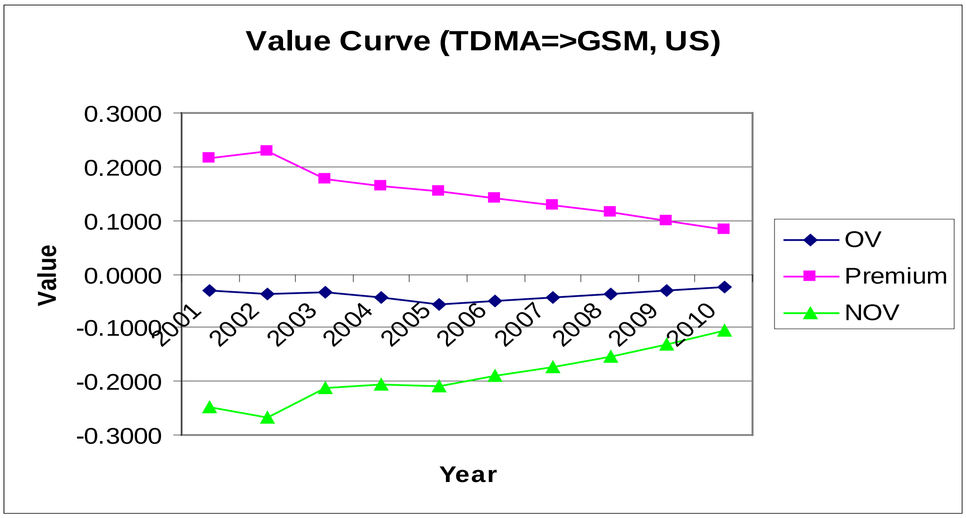


Figure 6.11 TDMA-GSM Scenario (US)

Another *2G* scenario (Figure 6.12) is the transition from *TDMA* to *CDMA* network technology. The premium value decreases rapidly and then decreases continuously because of *CDMA*'s popularity in the market. NOV is positive starting in 2001, and increases continually. NOV is achieved a peak in 2003 and then decreases gradually. So, the transition from *TDMA* to *CDMA* is most desirable in 2003 and less desirable after that, although NOV is positive.

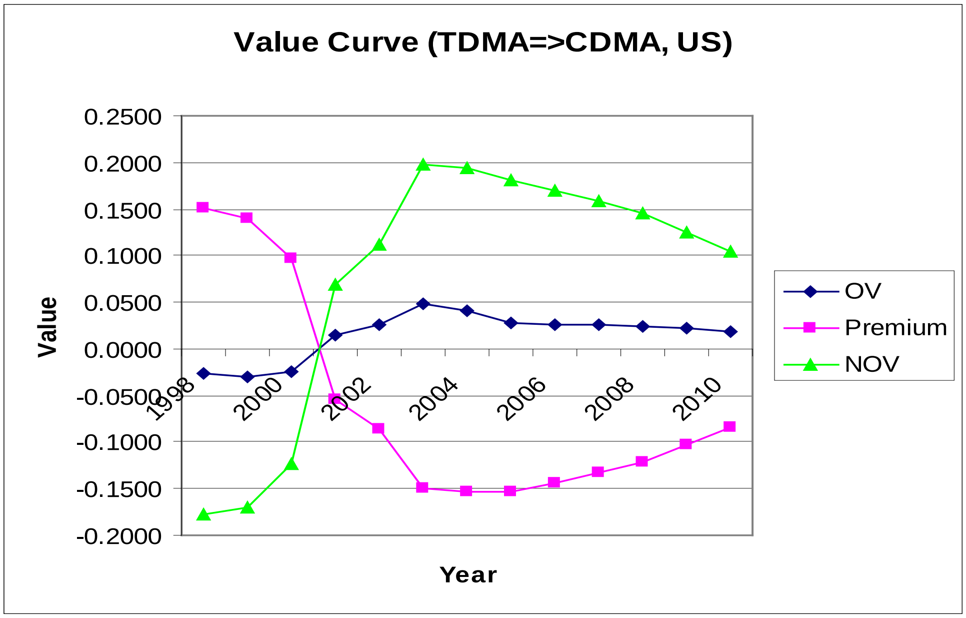


Figure 6.12 TDMA-CDMA Scenario (US)

- **Technology Transition toward 3G**

Moving from TDMA to *WCDMA* or *cdma2000* network technology is similar results because their market value is similar. Both diagrams (Figure 6.13 and 6.14) show that the transition is desirable starting in 2008 or later. These results can be translated that current TDMA is strong, so 3G technology will be delayed to deploy in the US market.

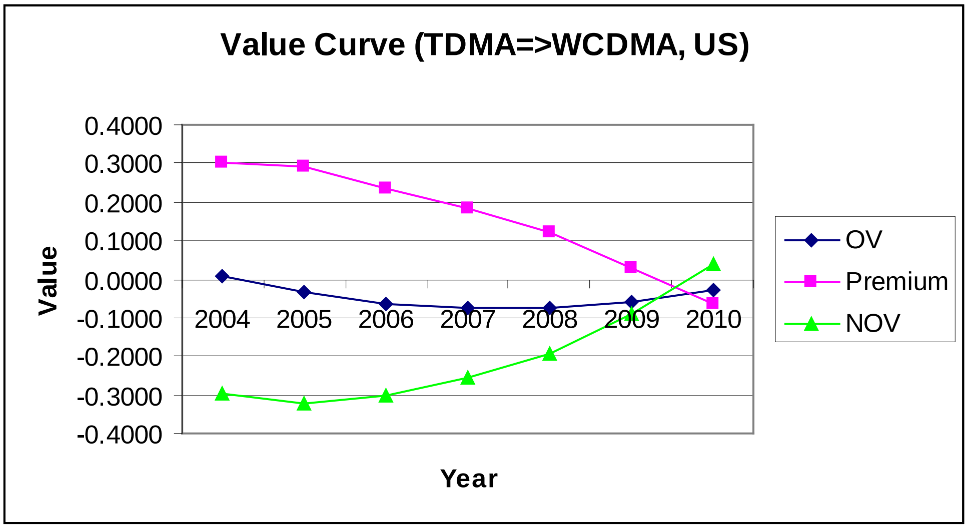


Figure 6.13 TDMA-WCDMA Scenario (US)

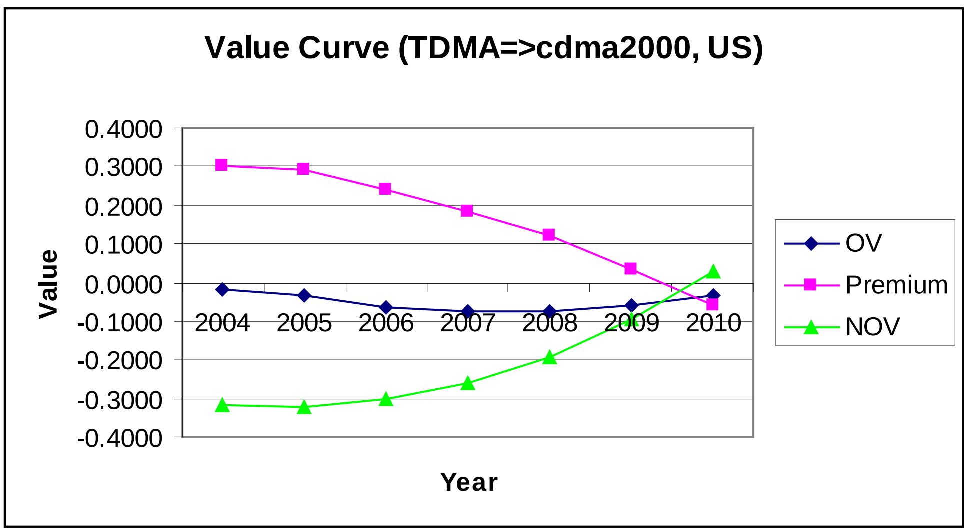


Figure 6.14 TDMA-CDMA Scenario (US)

Figure 6.15 shows the movement from *GSM* to *CDMA* network technology. This transition is recommended because the premium value is initially negative and continues to steadily negative and option value is positive continually. However, NOV decreases gradually after a peak of 2003. So, the transition to move *CDMA* from *GSM* is desirable. This result is completely different from world market. This difference is clear because *GSM* dominates the market (over 70%) in world, while *CDMA* is more popular than *GSM* in the US market.

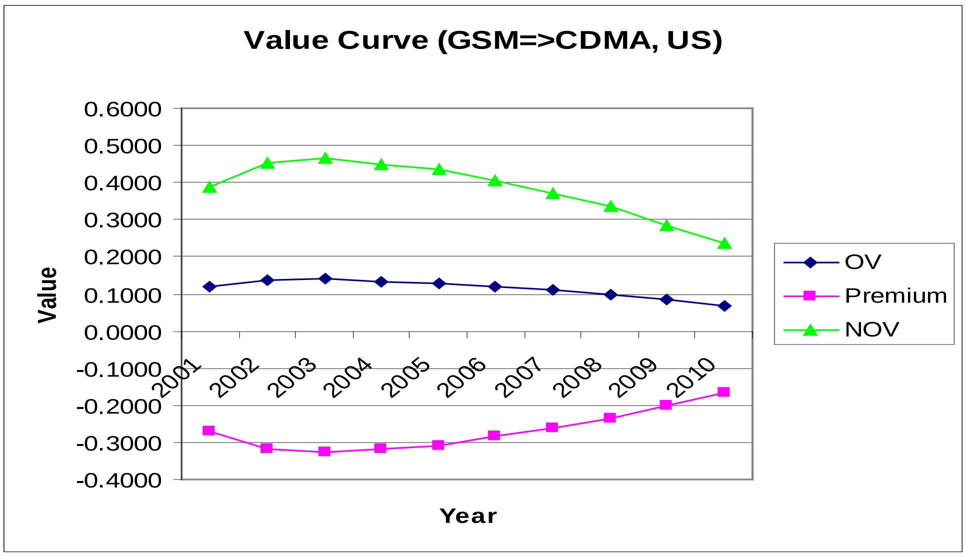


Figure 6.15 GSM-CDMA Scenario (US)

Figure 6.16 shows the transition from *GSM* to *WCDMA* (*3G*) network technology. The premium value decreases continuously, and finally is negative after 2008. The option value is steadily negative, but positive after 2009. NOV is initially negative, but highly increases and positive after 2009. So, the transition is desirable starting in 2009 or later.

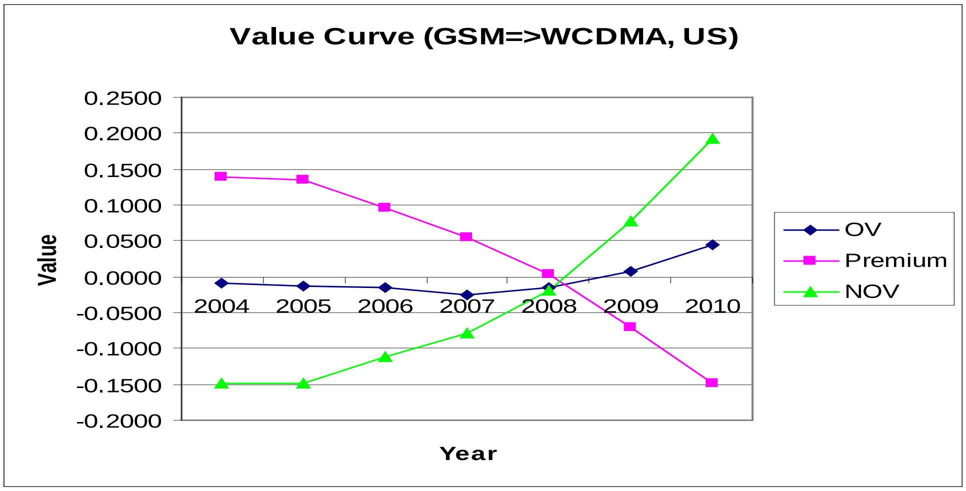


Figure 6.16 GSM-WCDMA Scenario (US)

Moving from *GSM* to *cdma2000* is the same with the transition from *GSM* to *WCDMA*, as shown in Figure 6.17. This is because *WCDMA* and *cdma2000* have similar market value or market share in US. So, the transition from *GSM* to *cdma2000* is recommended after 2008.

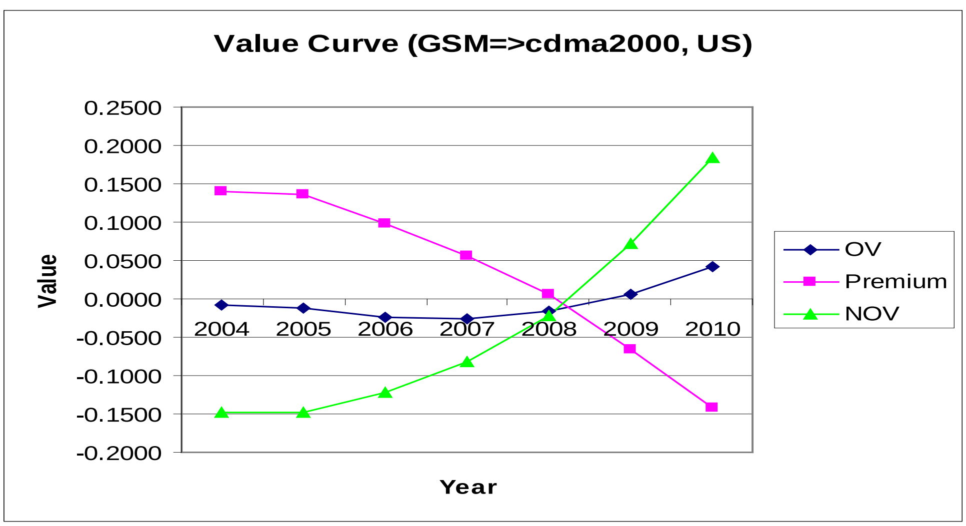


Figure 6.17 GSM-cdma2000 Scenario (US)

The next two scenarios (Figure 6.18 and 6.19) display the value curve when moving from *CDMA* to *WCDMA* or *cdma2000* network technology. These results show that the transition is undesirable because the premium value is positive continuously until 2010 (saturation point) and the option value is always negative. Since the net option value increases in the level of negative over time, so transition should be delayed or never.

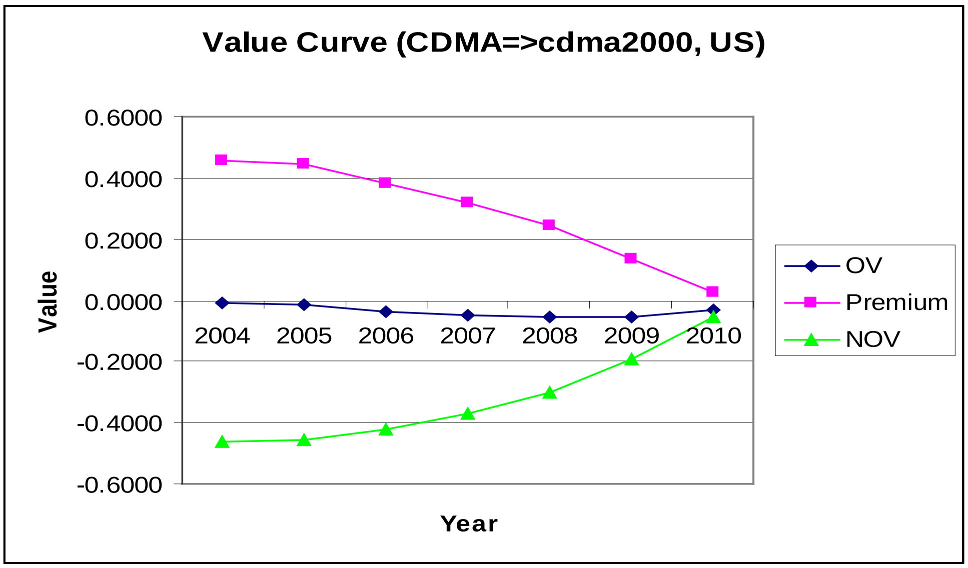


Figure 6.18 CDMA-cdma2000 Scenario (US)

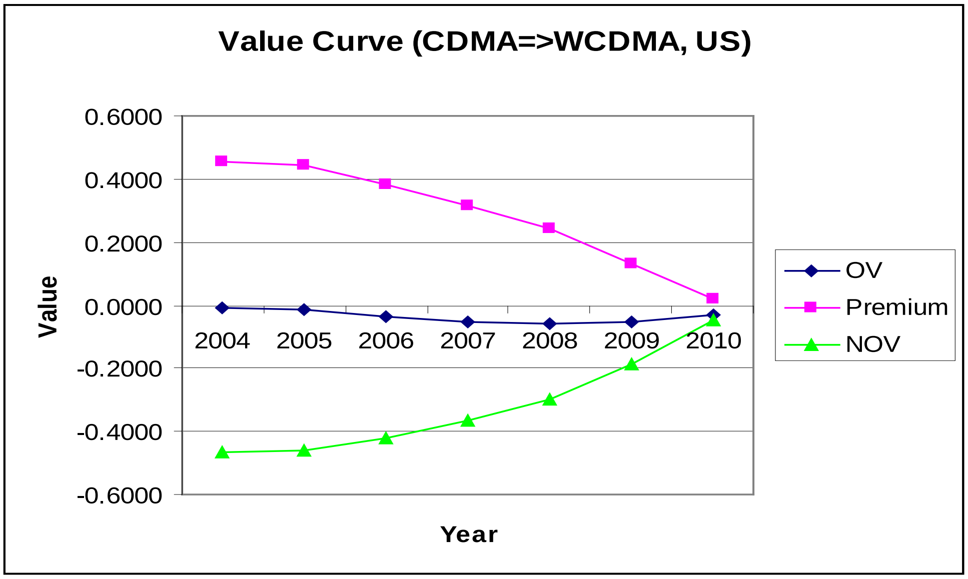


Figure 6.19 CDMA-WCDMA Scenario (US)

- **Sensitivity Analysis**

Figure 6. 20 shows three scenarios: 1) Scenario I, the base case, assumes WCDMA has 50% market share in 3G market, 2) Scenario II is a less optimistic case with WCDMA having only a 10% 3G market share, and 3) Scenario III is very optimistic with WCDMA at 90% market share.

The figure shows that the scenarios with higher WCDMA market share shifts the option value line positively and increases the value of technology transition to WCDMA from GSM, suggesting that early launching WCDMA (i.e., 2007 instead of 2009) is desirable. In contrast, the scenario with lower market share for WCDMA always results in negative option values and suggests that launching of WCDMA should be delayed indefinitely or not consider at all.

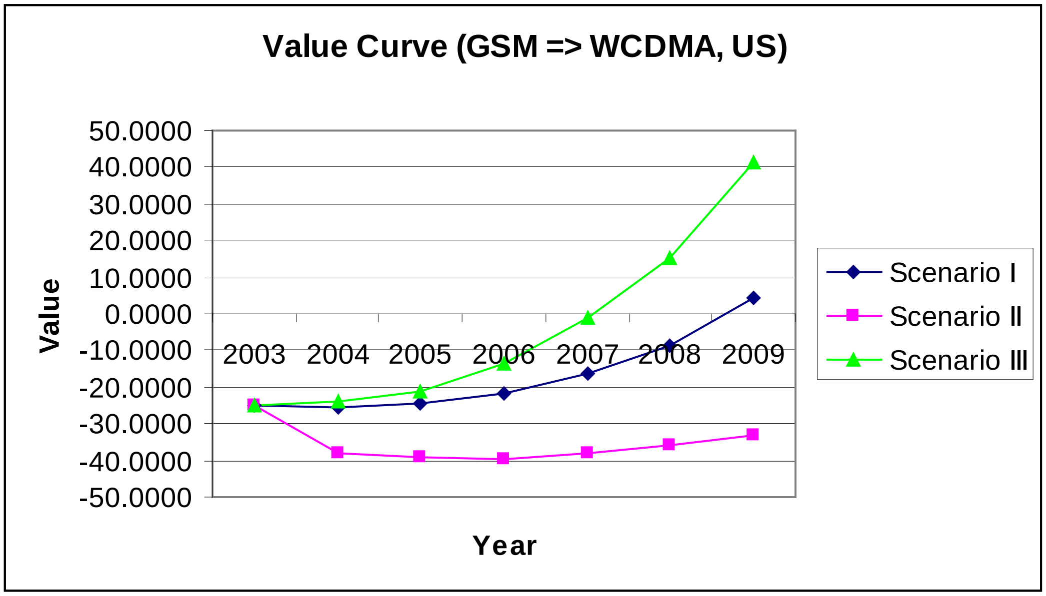


Figure 6.20 Sensitivity Analysis (GSM=>WCDMA Scenario)

The 'CDMA=>cdma2000 case considered three scenarios, shown in Figure 6.21, with the same market share parameters as the earlier 'GSM=>WCDMA case'.

Like the earlier case, the higher cdma2000 market share increases the value of technology transition, but the value never becomes positive in any scenario, indicating that transition from 2G CDMA to cdma2000 is never desirable during the analysis period that ends in 2010. However, the trend is continuously upward, so a future transition to cdma2000 may be considered.

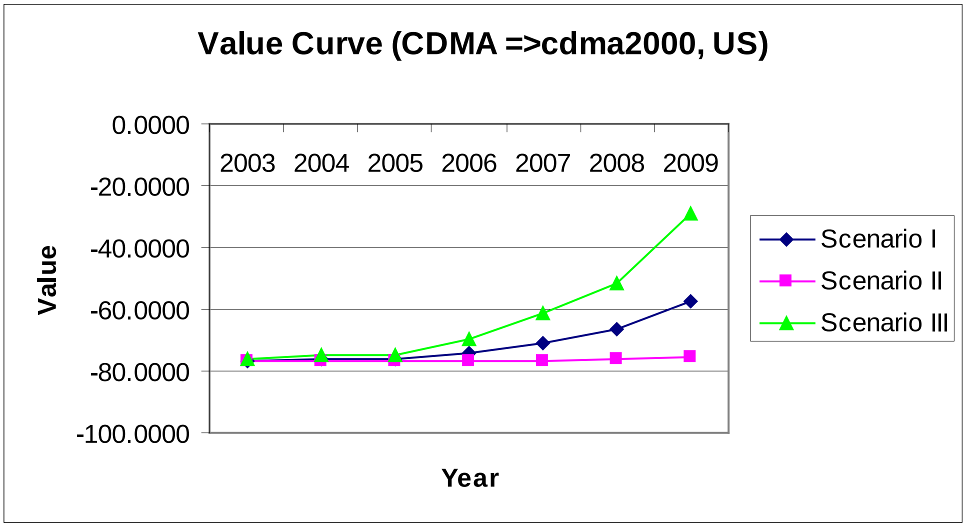


Figure 6.21 Sensitivity Analysis (CDMA=>cdma2000 Scenario)

6.3.2 Case of World

- **Inter-Generational Transition (1G=>2G)**

The first scenario is to move from Analog to *TDMA* network architecture. Figure 6.22 shows that the premium value (market dominance in current market) is gradually increasing by 1999, but after that it is abruptly decreased. While option value is negative at the initial stage, it gradually increases and is at its peak in mid-2001. Net option value is negative for a long time, but after 1999, it returns to a positive. This shows that the analog technology has been popular for a long time.

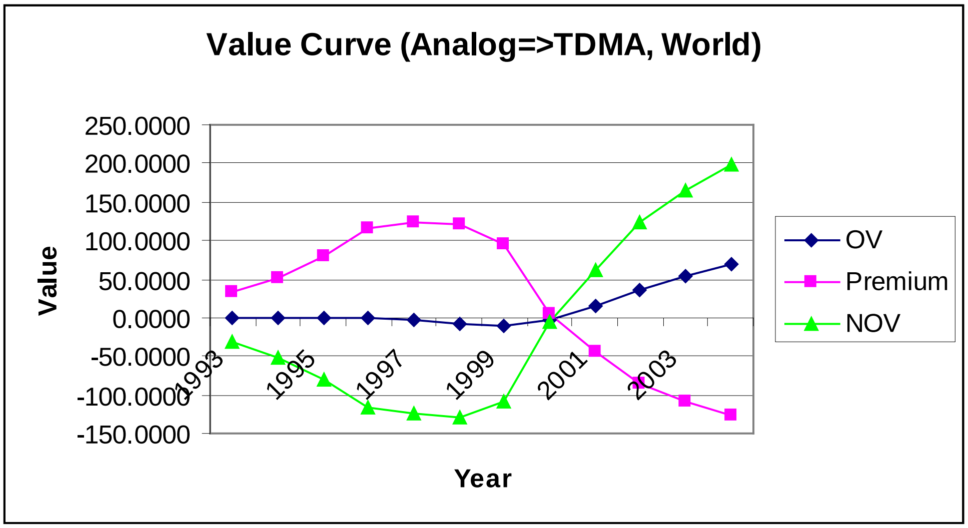


Figure 6.22 Analog-TDMA Scenario (World)

Figure 6.23 shows the results of moving from Analog to *GSM* network technologies. In this case, the result is much different from the previous case. The premium value is low, but the option value is high because of the high growth rate of *GSM* technology, resulting in a negative net option value until 2000, when it becomes positive. So, the transition from *1G* to *2G* is most desirable starting in 2000 or later.

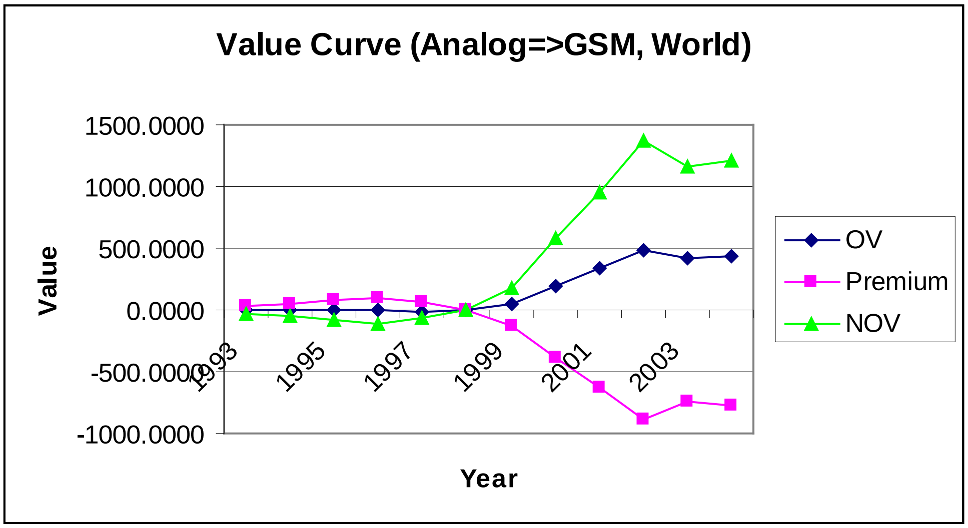


Figure 6.23 Analog-GSM Scenario (World)

Moving from Analog to *CDMA* network technology (Figure 6.24) is similar to the case of Analog to *TDMA* (Figure 6.19) because of the similar market penetration pattern between *TDMA* and *CDMA*. Likewise, the transition is most desirable starting in 2000 or later.

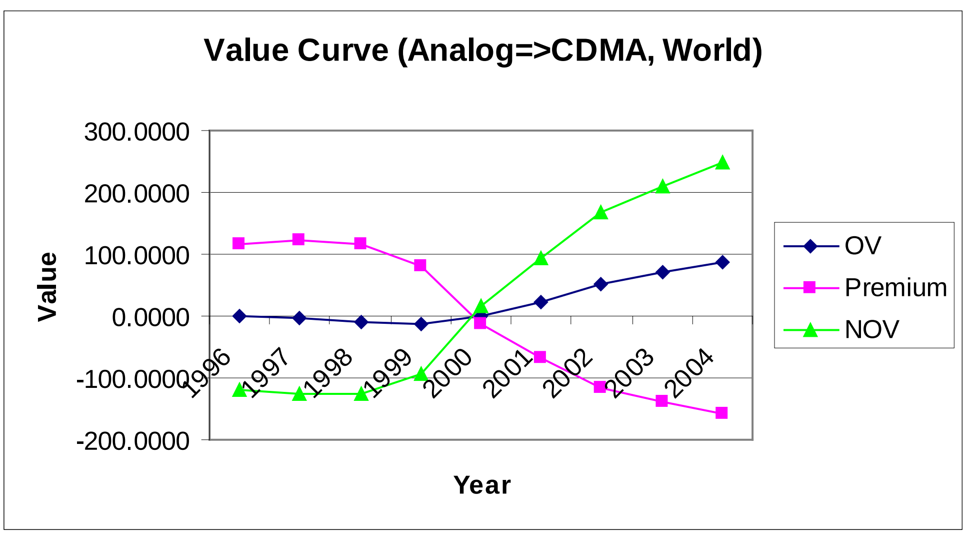


Figure 6.24 Analog-CDMA Scenario (World)

- **Intra-Generational Technology Transition (2G=>2G)**

The next scenario (Figure 6.25) displays the value curve when moving from *TDMA* to *GSM* network technology. This analysis shows that the transition is desirable because the premium value gradually decreases and the option value increases. Since the net option value increases over time, any transition should be delayed.

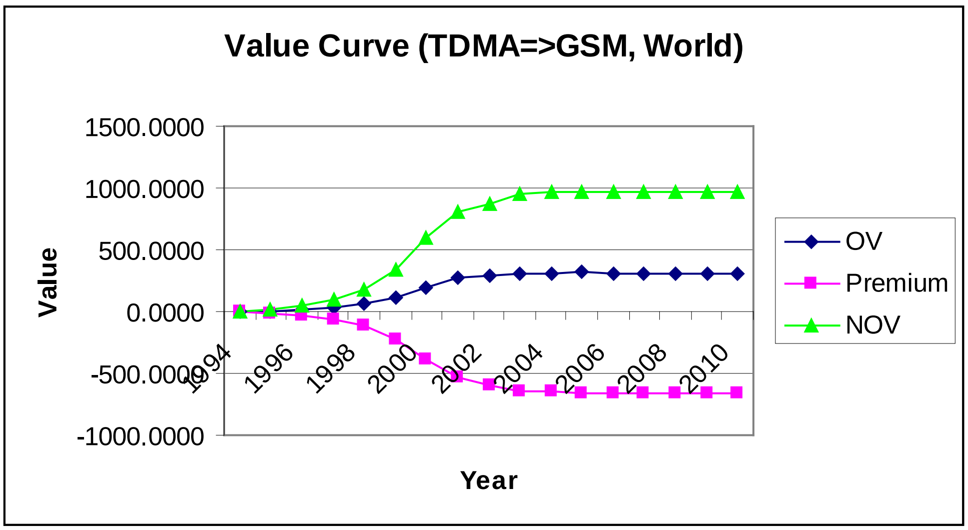


Figure 6.25 TDMA-GSM Scenario (World)

Another *2G* scenario (Figure 6.26) is the transition from *TDMA* to *CDMA* network technology. The premium value begins slightly positive and then decreases continuously because of *CDMA*'s popularity in the market. Net option value is positive starting in 1998, peaks in 2000, and decreases, although remaining positive, thereafter. The transition from *TDMA* to *CDMA* is most desirable in 2000, when net option value is at its peak.

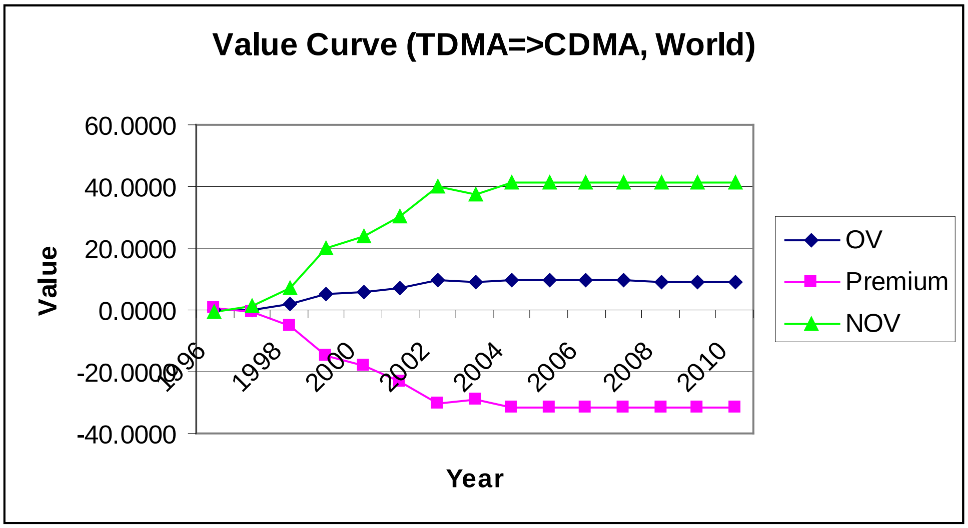


Figure 6.26 TDMA-CDMA Scenario (World)

Figure 6.27 shows the movement from *GSM* to *CDMA* network technology. This transition is not recommended because the premium value is initially high and continues to steadily increase. The conclusion not to proceed with the transition is clear because *GSM* dominates the market (over 70%) and competes with *CDMA* technology. So, *GSM* and *CDMA* providers will have no incentive to make this *2G* transition.

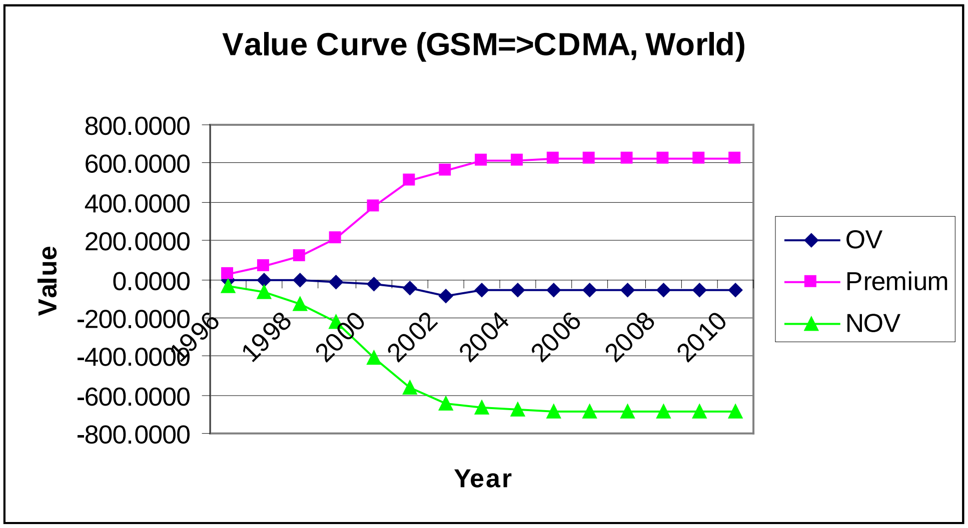


Figure 6.27 GSM-CDMA Scenario (World)

- **Technology Transition toward 3G**

Figure 6.28 shows the transition from *GSM* to *WCDMA* (*3G*) network technology. The results show that the transition is undesirable because the premium value is positive continuously until 2010 (the end of test period) and the option value is always negative. Since the net option value does not move up or down in the level of negative over time, so transition may be never. So, this scenario suggests that the operator does not consider it.

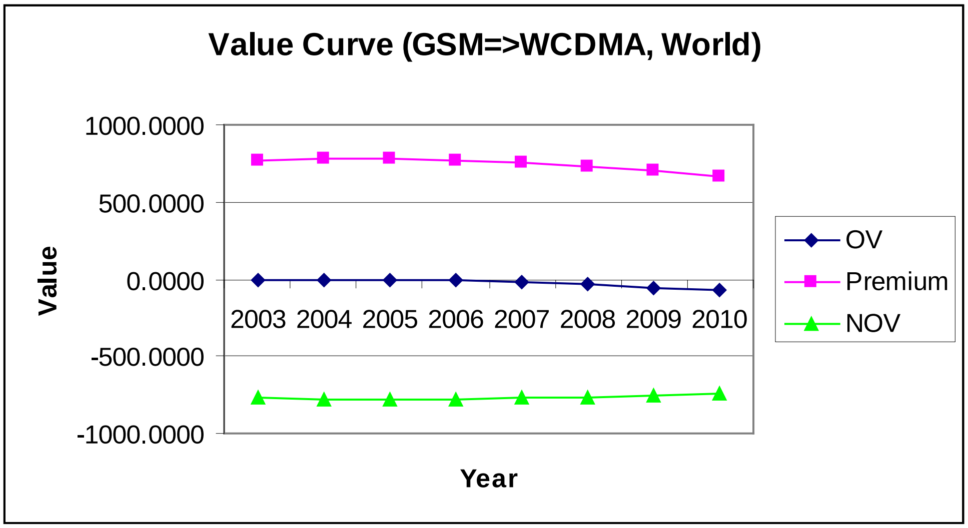


Figure 6.28 GSM-WCDMA Scenario (World)

Figure 6.29 shows the transition from *CDMA* to *cdma2000* (*3G*) network technology. The premium value decreases continuously, and finally is negative until 2010 (the end of test period). The option value is steadily negative, but since the reducing effect of premium is bigger that that of the option value, NOV is increasing continuously. But because finally NOV is still negative until 2010, the transition is not desirable with a possible positive after 2010.

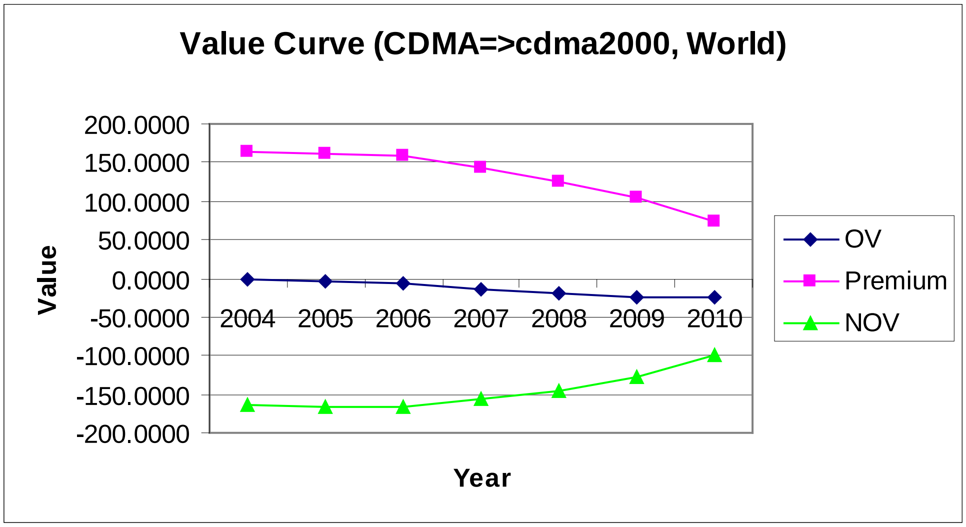


Figure 6.29 CDMA-cdma2000 Scenario (World)

- **Sensitivity Analysis**

Figure 6.30 shows the results of three scenarios using world market data and the same WCDMA market share assumptions as used in the case of the US market (Refer to Figure 6.17).

The higher WCDMA market share increases the value of technology transition, but the value never becomes positive in any scenario, indicating that transition from 2G GSM to WCDMA is never desirable during the analysis period that ends in 2010. However, the trend is continuously upward, so a future transition to WCDMA may be considered.

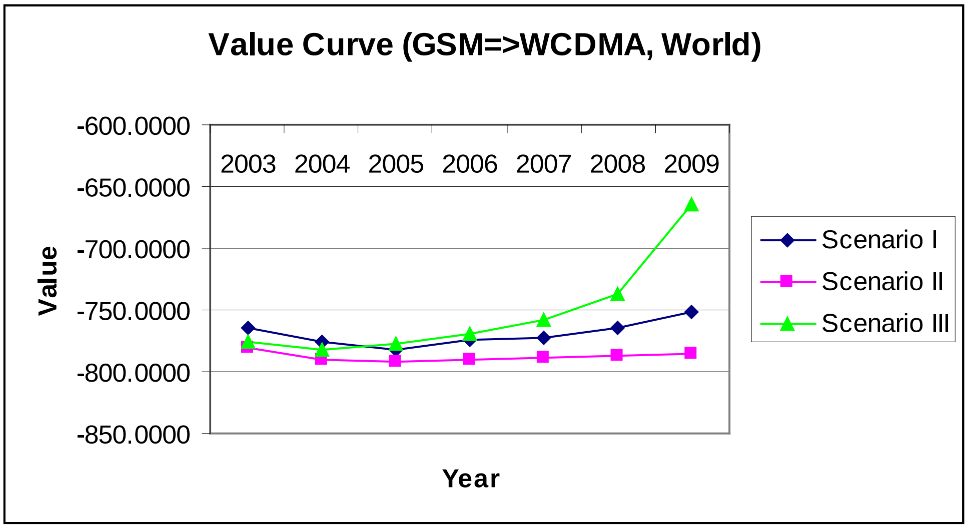


Figure 6.30 Sensitivity Analysis (GSM=>WCDMA Scenario)

In this case (Figure 6.31), a higher cdma2000 market share increases the value of technology transition similarly to some of the earlier cases using US data, but the option value remains negative in all three scenarios, indicating that transition from 2G CDMA to cdma2000 is not desirable at any time through 2010. However, the value becomes continuously less and less negative as the years pass, indicating that at some point, it maybe become positive and a transition to cdma2000 should be considered.

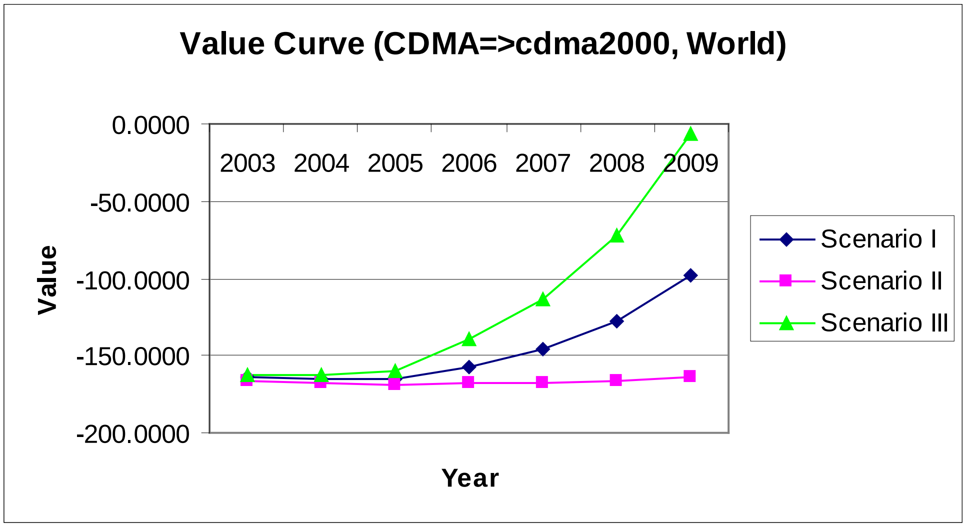


Figure 6.31 Sensitivity Analysis (CDMA=>cdma2000 Scenario)

6.3.3 Multi-stage Scenarios

Until now, one step technology transition cases are discussed. However, a firm's technology transition decisions are more complex and dynamic and must consider multiple technology migration paths. So, in this section, multi-stage technology transition cases are discussed.

As addressed in Chapter 2, there are two typical technology migration paths in network architectures for facilitating the movement from the current into the next generation network architecture. One path calls for 'Code Division Multiple Access (CDMA)-based network migration', which requires extensive infrastructure replacement, while the other path, 'Global Systems for Mobile Communications (GSM)-based network migration', requires the existing network to be upgraded. Based on these two migration paths, this study considers all possible migrations options even thought not all scenarios are currently practical.

7 GSM-based Migration Scenario

The first migration scenario, 'GSM-based Migration Scenarios', has supported in Europe. Since the European 2G standard is GSM and the Europeans are developing WCDMA as a 3G standard, one of the most common multi-stage technology migration paths will be 'analog-GSM- (GPRS-EDGE)-WCDMA'. This migration scenario is called 'the stepping-stone approach' because GSM will be upgraded to GPRS or EDGE as a 2.5G technology with only minimal changes. Most GSM network service operators prefer this approach because the cost is small and risk can be avoided. For this study, the 2.5G upgrades cannot be assessed because of the lack of available market data. However, the absence of this has little impact on the overall study because these two 2.5 technologies are complementary to GSM and do not require major architecture changes, but only minor upgrades.

In the US, the major TDMA operator, AT&T-Cingular, has chosen to adopt GSM. Their future plans are to move to GSM-GPRS, then to deploy GSM-GPRS-EDGE, and finally to adopt WCDMA. Other US TDMA operators are still deciding which migration path to pursue.

(1) 'Analog-TDMA-WCDMA' Migration Scenario

The first technology migration scenario is 'Analog-TDMA-WCDMA'. The technology transition option value from analog to TDMA is negative until 1999 and becomes positive in 2000 and remains positive until 2004 (see shaded area in the third column of Table 6.3). Anytime during this positive period, a firm can choose to migrate to 2G technology depending on its individual circumstances, such as financial condition, or on the market or economic conditions. Based on the analysis, the optimum migration year is 2003. Moving to WCDMA from TDMA is desirable starting in 2010 because the technology transition option value turns positive, and although this study's analysis period ends then, it is likely to remain positive for several years thereafter.

Table 6.2 'Analog-TDMA-WCDMA' Migration Scenario

Technology Transition Option Value

Year	Analog=>TDMA	TDMA=>WCDMA	Maximum
1998	-0.5215		-0.5215
1999	-0.2865		-0.2865
2000	0.0402		0.0402
2001	0.2212		0.2212
2002	0.3611		0.3611
2003	0.4741		0.4741
2004	0.4640	-0.2974	0.4640
2005		-0.3230	-0.3230
2006		-0.3019	-0.3019
2007		-0.2566	-0.2566
2008		-0.1924	-0.1924
2009		-0.0890	-0.0890
2010		0.0372	0.0372

(2) 'Analog-TDMA-cdma2000' Migration Scenario

Our next migration scenario, shown in Table 6.4, is 'Analog-TDMA-cdma2000. Naturally, the analog to TDMA transition option value is identical to the previous scenario with the optimum year being 2003. The TDMA to WCDMA transition is very similar to that of the previous scenario with a positive value starting in 2010.

Table 6.3 Analog-TDMA-cdma2000' Migration Scenario

Technology Transition Option Value

Year	Analog=>TDMA	TDMA=>cdma2000	Maximum
1998	-0.5215		-0.5215
1999	-0.2865		-0.2865
2000	0.0402		0.0402
2001	0.2212		0.2212
2002	0.3611		0.3611
2003	0.4741		0.4741
2004	0.4640	-0.3188	0.4640
2005		-0.3231	-0.3231
2006		-0.3026	-0.3026
2007		-0.2582	-0.2582
2008		-0.1956	-0.1956
2009		-0.0946	-0.0946
2010		0.0289	0.0289

(3) 'Analog-GSM-WCDMA' Migration Scenario

The 'Analog-GSM-WCDMA' migration path is analyzed in Table 6.5. Option value is positive for the analog to GSM transition in 2002 through 2004 with 2004 as the optimum year. GSM will continue until 2008 because the technology transition option value from GSM to WCDMA is negative. In 2009, the option value turns positive; so moving from GSM to WCDMA should be considered starting then. One reason GSM technology remains the dominant service for a long period of time is that GSM a proven, stable technology and 3G technology(WCDMA)'s future is still uncertain and its demand is limited.

Table 6.4 Analog-GSM-WCDMA' Migration Path

Technology Transition Option Value

Year	Analog=>GSM	GSM=>WCDMA	Maximum
2001	-0.1003		0.0000
2002	0.0726		0.0726
2003	0.1509		0.1509
2004	0.1924	-0.1482	0.1924
2005		-0.1478	0.0000
2006		-0.1108	0.0000
2007		-0.0794	0.0000
2008		-0.0192	0.0000
2009		0.0782	0.0782
2010		0.1928	0.1928

(4) 'Analog-GSM-cdma2000' Migration Scenario

The fourth migration scenario, 'Analog-GSM-cdma2000', includes the introduction of cdma2000, in place of WCDMA. Again, as shown in Table 6.6, analog to GSM results are the same as those in Table 8.4. Substituting cdma2000 in this case for WCDMA in the previous case results in very similar option values because, currently, GSM and CDMA each have about 50% of the US market share, and the forecasted market share for WCDMA and cdma2000 in this study is the same, and therefore, market value is also the same.

However, considering technological feasibility, the movement from GSM to WCDMA is more likely to occur than GSM to cdma2000 because of the technical difficulties to implement the latter. In this case, the transition from GSM to cdma2000 will occur later than that of GSM to WCDMA or not at all.

Table 6.5 Analog-GSM-cdma2000' Migration Path

Technology Transition Option Value

Year	Analog=>GSM	GSM=>cdma2000	Maximum
2001	-0.1003		-0.1003
2002	0.0726		0.0726
2003	0.1509		0.1509
2004	0.1924	-0.1482	0.1924
2005		-0.1481	-0.1481
2006		-0.1210	-0.1210
2007		-0.0812	-0.0812
2008		-0.0226	-0.0226
2009		0.0721	0.0721
2010		0.1840	0.1840

(5) 'Analog-TDMA/GSM-WCDMA or -cdma2000' Migration Scenario

Many wireless operators overlay TDMA with GSM architecture to smooth the transition toward 3G. Tables 6.7 and 6.8 show these results. The results of these two cases are totally different from the previous two cases. The transition from analog to TDMA/GSM is most desirable in 1996 and continues positive, to a lesser degree, until 1999. The analysis shows that moving from TDMA/GSM to WCDMA is at its peak in 2004 and decreases, although still positive, until 2010, the end of the study period. This result supports that TDMA carrier introduce GSM early in current networks and also WCDMA for a 3G service in the future.

Table 6.6 Analog-TDMA/GSM-WCDMA' Migration Scenario

Technology Transition Option Value

Year	Analog=>TDMA	TDMA=>WCDMA	Maximum
1996	0.8725		0.8725
1997	0.7244		0.7244
1998	0.5151		0.5151
1999	0.2635		0.2635
2000	-0.0732		-0.0732
2001	-0.3854		-0.3854
2002	-0.5485		-0.5485
2003	-0.6830		-0.6830
2004	-0.7045	0.4644	0.4644
2005		0.4547	0.4547
2006		0.4381	0.4381
2007		0.3742	0.3742
2008		0.2946	0.2946
2009		0.1905	0.1905
2010		0.0908	0.0908

Table 6.7 Analog-TDMA/GSM-cdma2000' Migration Scenario

Technology Transition Option Value

Year	Analog=>TDMA	TDMA=>cdma2000	Maximum
1996	0.8725		0.8725
1997	0.7244		0.7244
1998	0.5151		0.5151
1999	0.2635		0.2635
2000	-0.0732		-0.0732
2001	-0.3854		-0.3854
2002	-0.5485		-0.5485
2003	-0.6830		-0.6830
2004	-0.7045	0.4644	0.4644
2005		0.4550	0.4550
2006		0.4394	0.4394
2007		0.3858	0.3858
2008		0.3211	0.3211
2009		0.2263	0.2263
2010		0.0988	0.0988

8 CDMA-based Migration Scenario

CDMA carriers, Verizon Wireless and Sprint PCS, are considering to migrate to cdma2000-1x and its future derivatives, cdma-1xEV-DO and cdma-1xEV-DV, as an alternative to moving directly to 3G technologies. But still they have some factors to consider when migrating to WCDMA, for example, the majority owner of Verizon Wireless is Vodafone and Vodafone uses GSM in Europe. As a result, Verizon Wireless might choose WCDMA as its 3G service. So, in this study, any possible options are investigated.

(1) 'Analog-CDMA-cdma2000' Migration Scenario

The first CDMA-based scenario is 'Analog-CDMA-cdma2000', shown in Table 6.9. Most CDMA carriers want to migrate to cdma2000 because the transition requires minimal changes and cost. Both technologies use the same bandwidth (1.25Mhz), equipment can be retained, and only software upgrades are necessary.

The transition to CDMA from analog is desirable from 2001 to 2004, the optimal year. This result is similar to the GSM-based transition case because, in the US, the market share for these tw o technologies, a nd the r esulting ma rket va lue, is s imilar. Moving f rom C DMA to cdma2000 i s ne ver d esirable dur ing t he s tudy period be cause t he opt ion va lue i s ne gative throughout. Thereafter, the possibility exists that this transition will become favorable.

Table 6.8 Analog-CDMA-cdma2000' Migration Scenario

Technology Transition Option Value

Year	Analog=>CDMA	CDMA=>cdma2000	Maximum
1998	-0.5989		-0.5989
1999	-0.3442		-0.3442
2000	-0.0410		-0.0410
2001	0.2280		0.2280
2002	0.5418		0.5418
2003	0.6531		0.6531
2004	0.6978	-0.4645	0.6978
2005		-0.4587	-0.4587
2006		-0.4196	-0.4196
2007		-0.3693	-0.3693
2008		-0.3010	-0.3010
2009		-0.1909	-0.1909
2010		-0.0564	-0.0564

(2) 'Analog-CDMA-cdma2000' Migration Scenario

Another possible migration scenario, 'analog-GSM-WCDMA', introduces WCDMA instead of cdma2000. These results, in Table 6.10, are similar to the results in Table 8.8. Again, the market share assumptions are the same (50%) for WCDMA and cdma2000.

However, considering technological feasibility, the movement from CDMA to cdma2000 is mor e like ly to occur tha n CDMA to WCDMA because o f the te chnical di fficulties to implement the latter. In this case, the transition from CDMA to WCDMA will occur later than that of CDMA to cdma2000 or not at all.

Table 6.9 Analog-CDMA-WCDMA' Migration Scenario

Technology Transition Option Value

Year	Analog=>CDMA	CDMA=>WCDMA	Maximum
1998	-0.5989		-0.5989
1999	-0.3442		-0.3442
2000	-0.0410		-0.0410
2001	0.2280		0.2280
2002	0.5418		0.5418
2003	0.6531		0.6531
2004	0.6978	-0.4645	0.6978
2005		-0.4586	-0.4586
2006		-0.4190	-0.4190
2007		-0.3678	-0.3678
2008		-0.2982	-0.2982
2009		-0.1856	-0.1856
2010		-0.0484	-0.0484

7.0 DISCUSSION AND CONCLUDING REMARKS

7.1 CONTRIBUTION OF THE STUDY

The goal of this study is not to give absolute value for the choice of technology, but to provide a theoretical framework for supporting operators' strategic decisions by showing how value is quantifiable in the decision-making process. Wireless network operator's options for technology migration are identified towards the next generation network architecture and present alternative migration strategies. However, one technology is not supported over another or one 3G-migration path over another. Rather, the challenges and advantages that operators may face in deploying new technologies are discussed.

This dissertation also addressed an important concept that has a high relevance in the current network environment. Exploring the multidimensional nature of strategic technology migration gives some implications in the development of network infrastructure of network carriers. The main theme of this study is 'the Real Options to Networks'. That is, this study introduces a new perspective, 'the real options approach (ROA)', when considering network-related issues, such as network architecture and technology choice, network service provisioning, and network regulation and policy. ROA considers potential opportunities and uncertainty as a positive value. Based on ROA, operators may find it worthwhile to evaluate new technology as a strategic option. This study raises core issues concerning the 3G transition and to resolve these issues on both qualitative and quantitative bases.

The fundamental importance of real options has been recognized in academics and in actual practice, such as the studies of technology management and strategic management fields, as an important factor when making critical business decisions. However, the use of real options to reframe one's approach for solving problems or to build additional flexibility into systems has been neglected.

This dissertation is one of a very few studies that assesses wireless network technologies using the real options approach, specifically switching options. We attempt to develop and present explicitly the importance of the link between the real options approach and technology management in networks. . This study not only provides valuation theory for various technology options in wireless networks, but also analyzes the strategic decision of choosing among them.

The main contribution of our study is to introduce options thinking to network managers for managing technology and innovation in networks. Network technology choice involves not only engineering issues but also strategic management issues.

Another important contribution of this study is its empirical validation of the strategic flexibility constructs and empirical testing of the value of network technologies in wireless networks. The notion of real options is tested using the world and US wireless network industries. A relatively simple framework was used, but the results are meaningful. The results of the data collected from world or US wireless industry data provides ample support for the validity and reliability of the constructs introduced in this study.

Consequently, this dissertation should direct network operators to begin thinking in terms of the available technology options and to maximize overall gain in their networks in highly uncertain network environments.

7.2 SUMMARY OF THE STUDY

The results obtained from the model provide several important insights. The most important findings and implications of this dissertation are detailed below.

7.2.1 Findings

The study examined the evolutionary characteristics of wireless technologies and assessed the value of technology migration using real-options framework. We developed a model for evaluating technology transition when a network operator holds options in technology choices, switching one for another technology in the firm. We use this model to assess wireless technology transition scenarios, such as inter-generational technology transition from 1G to 2G or 2G to 3G and intra-generational technology transition scenarios.

Figure 7.1 summarizes the results of all technology transition scenarios analyzed in this study including valuation and timing. For example, moving from analog to any 2G technology is desirable; however, the best choice for analog carriers is to move to CDMA in 2004 because it results in the highest option value (0.6978) of the three possibilities. It is not desirable for the TDMA carrier to move into GSM because all transition values are negative. But CDMA is desirable because of the positive option value of 0.1972 in 2003.

Concerning the transition from TDMA to 3G technologies, there is not much difference in transition option value between WCDMA (0.0372) and cdma2000 (0.0289) in 2010. In the case of GSM carriers, moving to 2G CDMA is recommended because of the positive transition option value (0.4654) in 2003, but in reality, this transition costs are excessive and the technologies are incompatible. This is a limitation of this study since only market data is available for technology assessment.

As with TDMA, the transition from GSM to 3G has a similar positive option value for WCDMA (0.1928) and cdma2000 (0.1840) in 2010. However, the majority of the GSM carriers is from Europe and only considers WCDMA migration for technical and political reasons. CDMA carriers do not consider 3G until 2010 because of the continuing negative transition values, but the transition will occur some time after arriving at the saturation point of current 2G CDMA market.

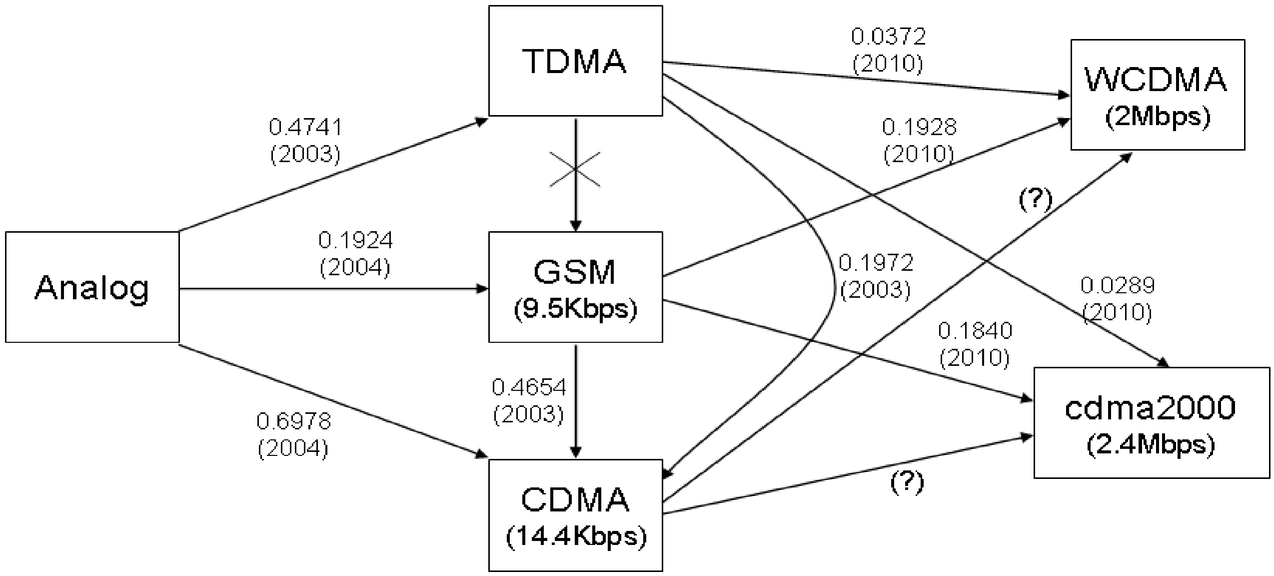


Figure 7.1 Technology Migration Path Diagram

Table 7.1 summarizes the results of all the scenarios using US and world data previously presented. In the inter-generational technology transition cases, i.e. 1G => 2G, positive option values are achieved during the analysis period for both US and world cases and therefore migration to 2G is recommended. Only the timing of the transition differs between the scenarios. For example, the analog => GSM scenario shows transition in the US in 2000 while in the world shows 1997. The earlier transition in the world market is because GSM is the established standard in Europe, the biggest market in the world, while GSM is in its early development stages in the US.

For the intra-generational technology transition cases, results are more complicated. In the US, the transition from TDMA to GSM is not recommended during the analysis period and moving to TDMA to CDMA is recommended but delayed until 2002 because of the current popularity of TDMA technology. Furthermore, transition from GSM to CDMA is not recommended in the US during the analysis period because CMDA is also popular in the US. For the world market, the early transition from TDMA to GSM and CDMA is recommended, 1996 and 1997, respectively, because GSM is popular in Europe and CDMA is also popular in Asia and the US. Since market share for GSM is larger than that of CDMA, the option value is not positive and therefore transition from GSM to CDMA is not recommended for either the world or US markets.

Finally, for both world and US markets, the transition toward 3G is not recommended during the analysis period because 3G is not as popular due to its greater uncertainty in the future, except in the US case for moving from GSM to WCDMA where a 2009 transition is desirable. These results may be different if 3G technologies are proven and become more widely accepted in the market.

Table 7.1 The Comparison of Results

Classification	Inter-generational Transition			Intra-generational Transition			Transition toward 3G	
	Analog-> TDMA	Analog-> GSM	Analog-> CDMA	TDMA-> GSM	TDMA-> CDMA	GSM-> CDMA	GSM-> WCDMA	CDMA-> cdma2000
US	Yes (2000)	Yes (2002)	Yes (2000)	No	Yes (2002)	No	Yes (2009)	No
World	Yes (2001)	Yes (1999)	Yes (2000)	Yes (1996)	Yes (1997)	No	No	No

7.2.2 Results Implication

The model developed for this study and its empirical results provide several indirect but important insights for current 2G wireless operators who are considering migration to 3G networks.

The results show that the evolution of wireless network technologies between generations is desirable, but transition is not desirable within generations (i.e. *TDMA* to *GSM*, or *GSM* to *CDMA*). As a result, from a strategic perspective, network service providers should consider the possible challenges that may hinder migration, such as the many uncertainties in markets and technologies. By identifying these challenges, network service providers can be more watchful of transition pitfalls and can choose a better alternative. Based on the results, the better path can be chosen depending upon their specific circumstances.

The primary implication of study results are as follows:

i. The transition between generations, i.e., Analog to TDMA, or, GSM, or, CDMA, is desirable, while the transition within the same generations, i.e., TDMA to GSM, or CDMA, and GSM to CDMA, is not desirable.
ii. The timing to migrate is different for each technology.
iii. Through this study, firms can learn about the extent of the transition between technologies by choosing among the available technologies and using the mix-and-match feature of market scenarios.

7.2.3 Migration Implications – Strategic Choices

As the various wireless technologies (TDMA, CDMA, and GSM) emerge and battle for being a global standard, wireless operators and equipment vendors aim to ensure the viability and dominance of their respective technology as the market evolves.

The migration strategies of wireless service operators are dependent on many factors, such as spectrum availability (or licenses), the firm's financial situation, market conditions (competition, subscribers maturity, and market size), the price and features of handsets, etc. These factors are difficult to quantify; however, the study model assumes that the option value reflects these factors implicitly as elements of uncertainty and is therefore meaningful. Three key factors are discussed in this dissertation:

(3) First, because of the large sunk investments in the existing networks, operators may prefer to upgrade gradually instead of abrupt replacements when moving to higher speed data services because it is a low-risk and cost-effective way to capitalize on the existing infrastructure.
(4) Second, with the high costs associated with 3G spectrum license acquisition, especially in Europe, wireless operators may attempt to operate within existing spectrum allocation and/or develop services within new spectrum.
(5) Third, wireless operators are concerned with global roaming for users across different networks, either using common 3G spectrum across regions or operating devices in multi-spectrum environments.

World Wireless

The move to 3G, CDMA-based networks will dominate, whether it is current 2G CDMA networks evolving to cdma2000 or the GSM/TDMA eventually moving to WCDMA.

At present, as shown in Table 7.2, the geographical picture is more straightforward with WCDMA poised to become the first truly global mobile communications standard, accepted on all continents and major countries. On the other hand, cdma2000 is unlikely to have any influence at all in Europe and only a modest presence in the increasingly important the rest of world region.

Table 7.2 Standard Situation for 3G Deployment

Region	WCDMA	Cdma2000
Europe	Mandatory	Not Present
North America	Backed by GSM carriers	Main for Incumbents
Asia	Strong Support	Substantial inroads

In the case of Europe, the TDMA-based GSM standard for mobile wireless enabled an initial proliferation of cellular usage and an apparent benefit to the region's wireless carriers and consumers. However, the subsequent market dominance of GSM put European wireless operators in the difficult position of being unable to easily take advantage of the superior technical features of CDMA once this technology became commercially viable.

In the US, on the other hand, the lack of a unified cellular standard created an incentive for wireless operators and equipment vendors to develop innovative new techniques, thus leaving the market as the ultimate technology arbiter. Thus, a CDMA became a commercial reality, wireless operators in the US were able to develop wireless networks based on this technology. Since it is now quite clear that 3G networks will be CDMA-based, the CDMA wireless operators stand better situated on a cost-effective, less technically complicated migration path.

US Wireless Carriers

TDMA carriers in the US, such as Cingular-AT&T and T-Mobile, have already introduced GSM as a first step toward conversion to WCDMA. If operators only consider the global market, then WCDMA may be the transition route they choose despite the higher cost than cdma2000. GSM currently dominates the world, and therefore, WCDMA is the logical transition from GSM, so WCDMA may be an appropriate transition in the US.

In its ultimate goal to implement a 3G broadband environment, Cingular-AT&T Wireless is quickly upgrading its networks and building a GSM/GPRS overlay over its current TDMA network. This would allow the company to provide data services using GPRS technology, which it eventually needs to easily transition toward 3G. The migration from current TDMA to WCDMA, is highly risky and expensive, but the competitive disadvantage of not upgrading, thereby not providing 3G wireless services, is significant.

Because of the costs and difficulties involved, Cingular-AT&T Wireless will not upgrade everywhere at once. Instead, the company will initially upgrade networks in key areas, and then spread those upgrades out into secondary markets. That means carriers will have to support older infrastructure while implementing the new. Cingular-AT&T Wireless, along with its competitors, would need to provide and sustain nationwide services on a network consisting of many different technologies. Doing that will require significant capital outlays and it must be transparent to the customer. That, in turn, means that Cingular-AT&T Wireless phones may, for a while, have to support as many as five different standards - from analog to TDMA, GSM/GPRS, EDGE and WCDMA.

Cingular-AT&T Wireless' decision to migrate to 3G services by overlaying GSM channels into its existing TDMA networks is significant. In fact, the viability of TDMA will be limited by its failure to increase its global presence. It is generally expected that Cingular-AT&T Wireless will use its EDGE deployment as an interim move in migration to wideband-CDMA (or WCDMA). WCDMA will allow for integrated voice and data service and will finally provide the carrier with the capacity advantages of CDMA technology. But what will become of the spectrum previously dedicated to EDGE? The very real risk is that the spectrum will have to be maintained for some time as a legacy network. This is because various enterprises may build costly and complex systems that include data communications using EDGE as an integral part.

Existing US CDMA carriers, Verizon Wireless and Spring PCS, have a great incentive to move to cdma2000 because of the lower cost and ease of upgrading. Sprint PCS has announced a detailed migration plan towards cdma2000 and will launch the nation’s first deployment of cdma2000-1XRTT, an advanced 2.5G service providing segregated capacity for data. Verizon Wireless, with 27% share of the US wireless market, has a significant stakeholder in the European carrier, Vodafone, whose migration strategy incorporates WCDMA. Verizon Wireless installed cdma2000-1XRTT in the fourth quarter 2003 and is ultimately expected to migrate to a system that can integrate with Vodafone.

7.3 LIMITATIONS OF THE STUDY

Interpretations of the results presented in this study are subject to some limitations and limit its general applicability. Although many limitations and weaknesses of this dissertation exist, only two main limitations are discussed and others are not presented here.

The most obvious limitation of this research is that it is based on very little empirical data. No matter how useful the simulation and our real options model are, they simply can not replace good quality evaluation based on large amount of data.

Finally, to solve the technology transition problems, there are several factors to be considered, such as technological factors (e.g., compatibility between technologies, easiness for implementation, etc.) and market factors (market size and share, data of revenues and costs, competition, etc.). However, the only available data is market data with size and share in our study as a historic data. The study also does not consider the compatibility of technologies, even though it is an important issue when technology transition is addressed. The assumption in this study is that the there is no difference in migration cost or complexity. This assumption limits the validity of the results. Thus, as more data become available, the more good quality of the model design and the choices of parameters.

The usefulness of this study is also severely limited by the fact that it is conducted in the context of specific area, especially US wireless industry, even though US is totally different environment from Europe or Asian countries. That is, the nature of the sample makes it difficult to generalize the results. There are different wireless technological environments in the US, Europe, and Asia. The US is allowed multiple standards, but Europe and Asia have a single standard, like GSM in Europe and CDMA in some Asian countries. If these geographical characteristics are to be considered, then a more complex analysis model is required. For example, in Europe and Asia, competition is not a factor in technology choice, while government policy will be more important factor.

7.4 FUTURE RESEARCH

The possibilities for future research on topics related to strategic technology management using the real options approach are extensive. Of them, a few of the possible extensions of the ideas covered in this dissertation. There are two main categories for the types of researches that will stem from this dissertation: 1) theory and model development of real options and 2) the application of our model to other technology-oriented industry to solve technology management problems.

First, real option research is still very much a growing area. Thus there is much more that needs to be done. Although the conceptual foundation for real options is well established, there is scope for further research extensions to some of the basic theories, especially relating to valuation techniques. Options involving real technology choices and strategies are generally much more complex than simple financial options in stock market. First, the uncertainty may be due to several variables instead of simply one variable such as the price in financial options. Further, it may not always be easy to measure the value of underlying assets because of its dynamics and never traded in the market. These complexities may not allow one to find exact valuation model.

The other future research to come from this dissertation will be the application of our real option theory and techniques to a variety of other industry to solve technology management problems, such as high-tech industry and medical industry. Conceptually any technology choice decision where significant uncertainties are present can be considered our strategic technology transition model using the real options approach.

7.5 CONCLUSIONS

The main theme of this study is 'the Real Options to Networks'. That is, this study introduces a new perspective, 'the real options approach (ROA)', when considering network-related issues, such as network architecture and technology choice, network service provisioning, and network regulation and policy. ROA considers potential opportunities and uncertainty as a positive value. Based on ROA, operators may find it worthwhile to evaluate new technology as a strategic option. This study raises core issues concerning the 3G transition and to resolve these issues on both qualitative and quantitative bases.

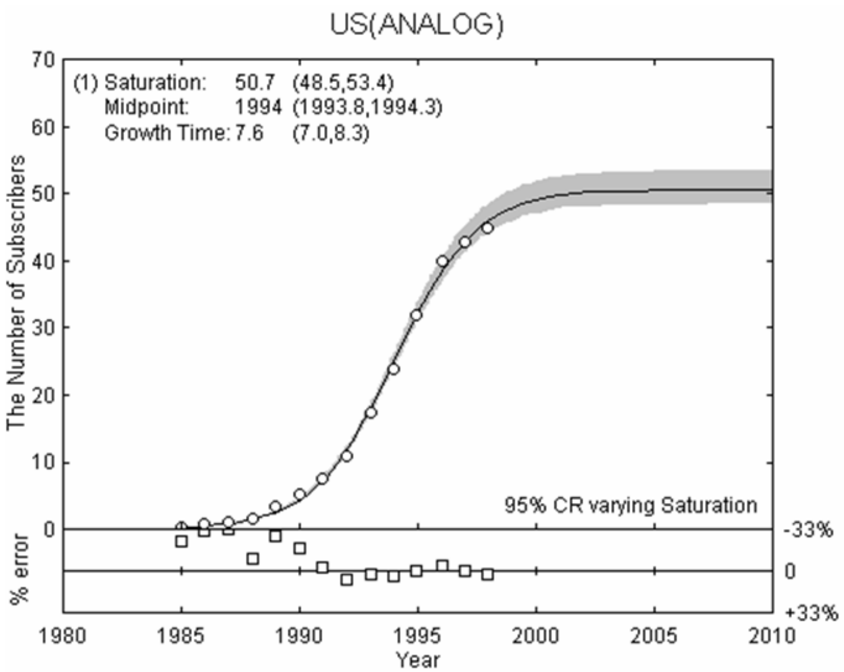
This study proposes a theory to show technology options to migrate to new technology from old technology using the real options approach (ROA). We also develop a model to assess explicitly the value of technology transition options (i.e., technology choice) on a firm's technology strategy in the wireless industry.

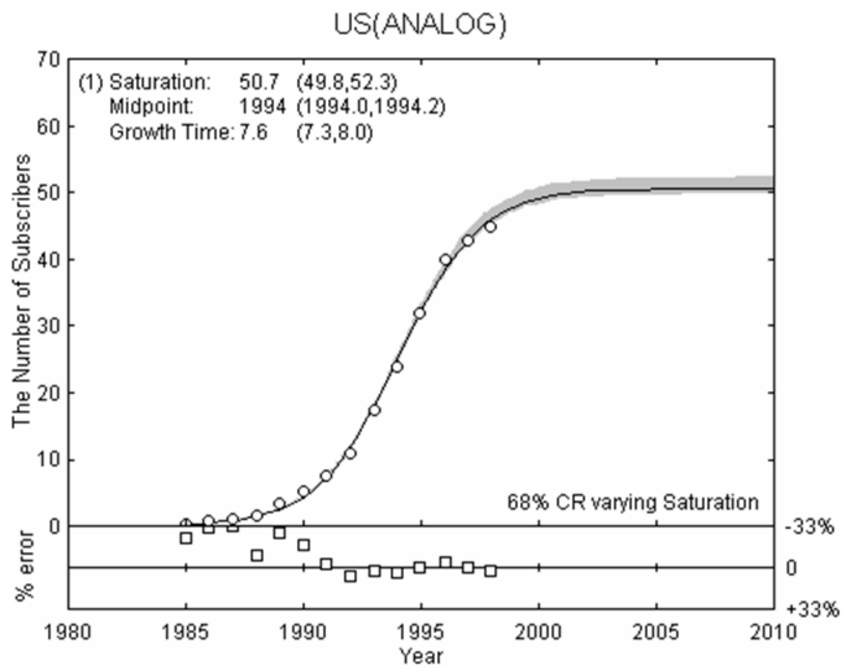
Finally, the findings of the study imply that strategic technology choice is extremely important determinant of firm's competitiveness. Exploring the dimensions of strategic decisions proved to be valuable, as the study found that it is important for a firm to have strategic flexibility is extremely high for improving a firm's value. The study also found that strategic technology choice is important regardless of the level of environmental uncertainty faced by the firm. Since the next generation wireless network technologies and architectures are still a subject of debate with no substantial implementation results, there is much work to do. With the further research, the scope of study can be expanded.

APPENDIX A

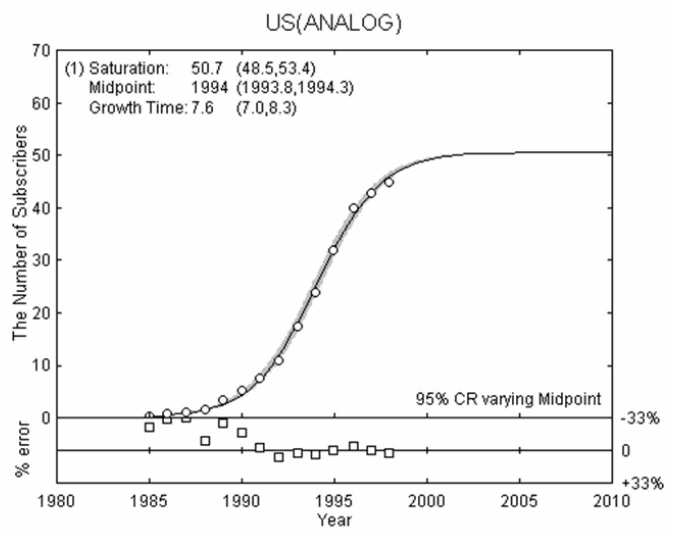
1. Confidence Interval of Market Forecasting

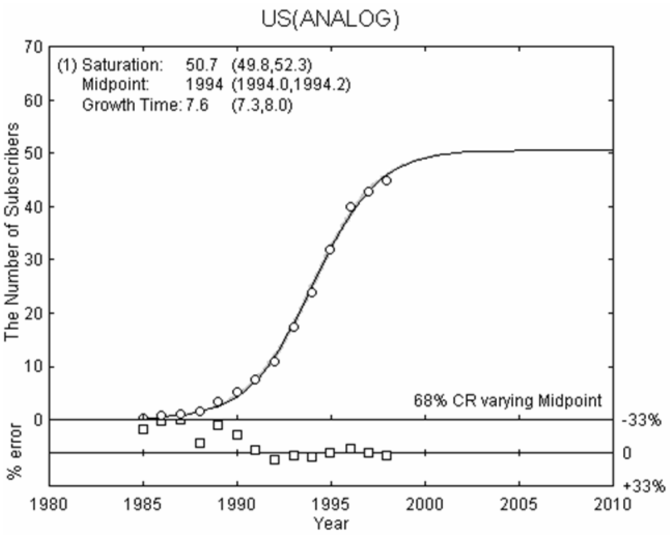
1) US Analog (95% and 68% CI – varying saturation)



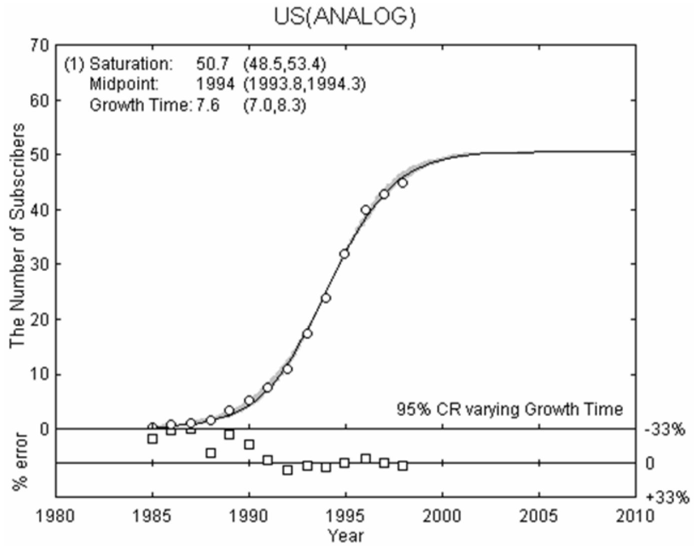


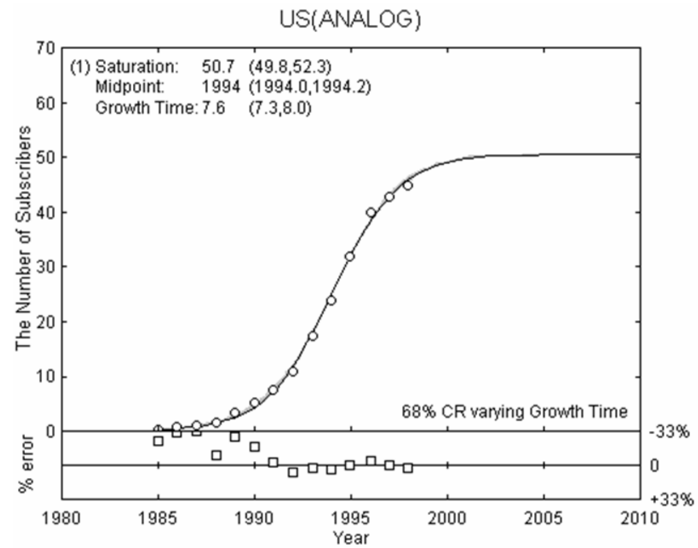
2) US Analog (95% and 68% CI – varying midpoint)



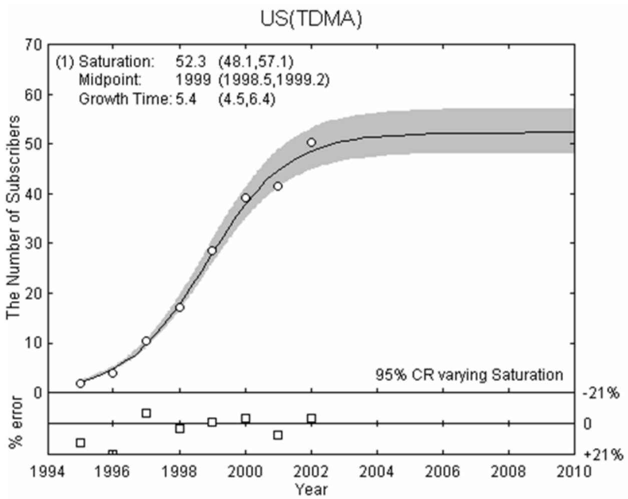


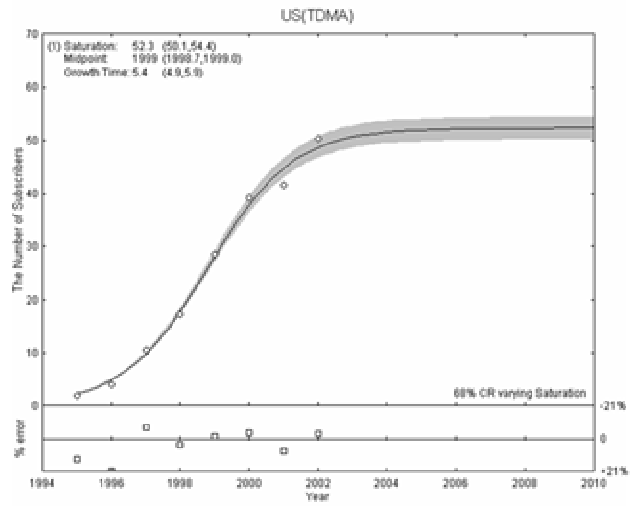
3) US Analog (95% and 68% CI – varying growth time)



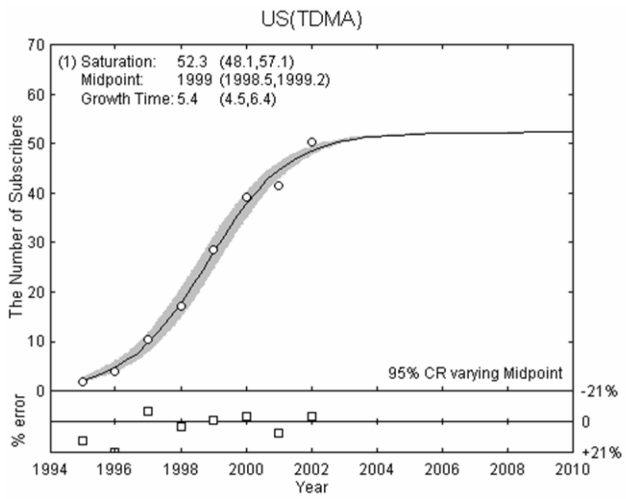


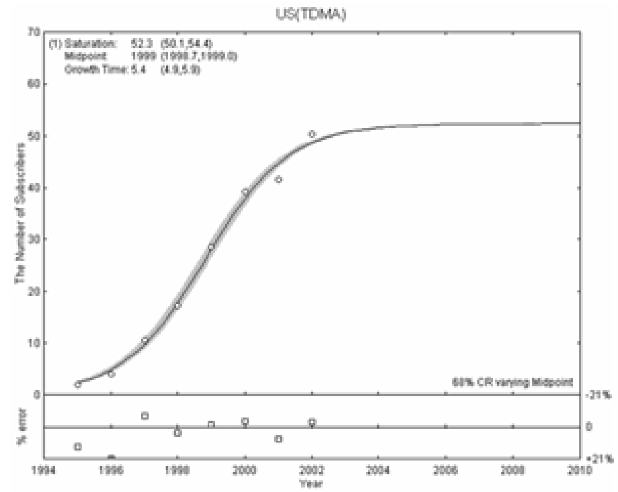
4) US TDMA (95% and 68% CI – varying saturation)



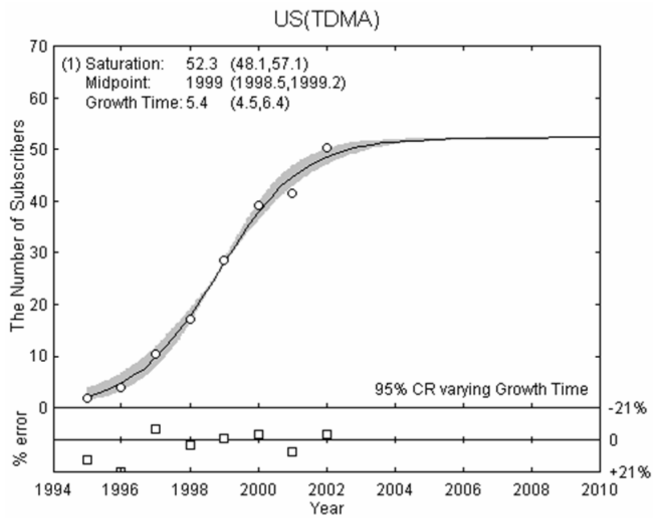


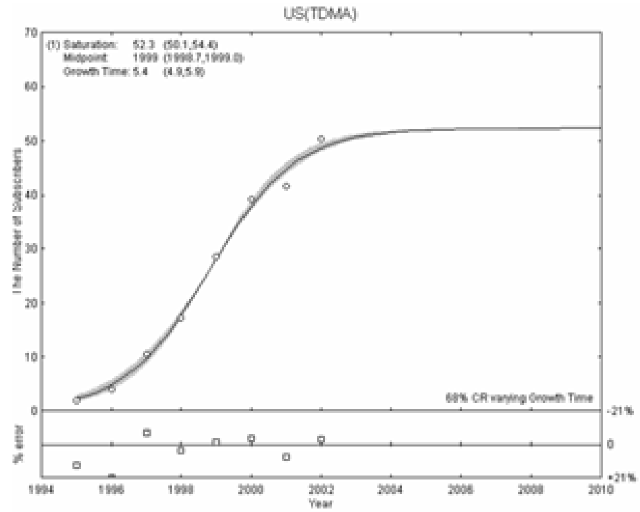
5) US TDMA (95% and 68% CI – varying midpoint)



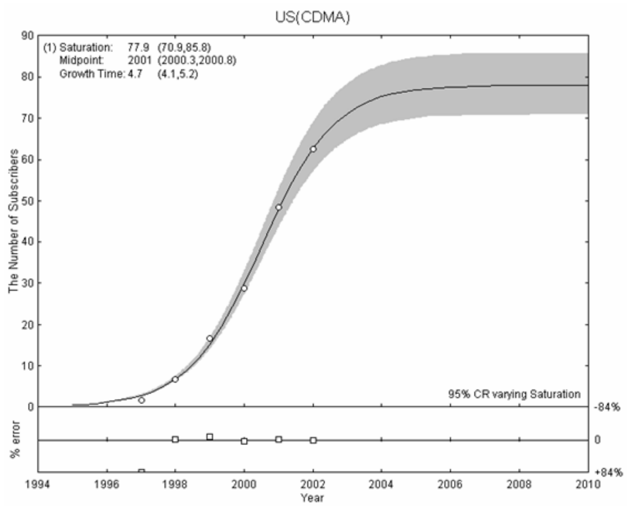


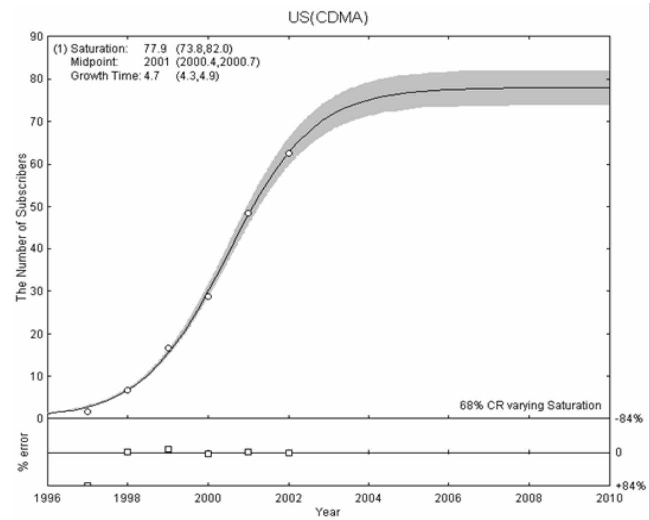
6) US TDMA (95% and 68% CI – varying growth time)



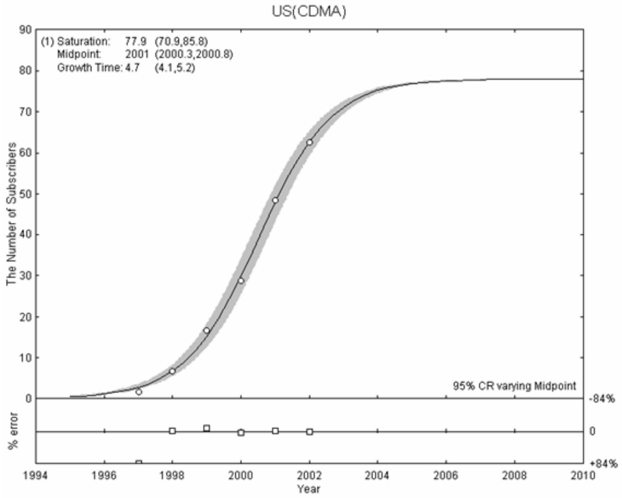


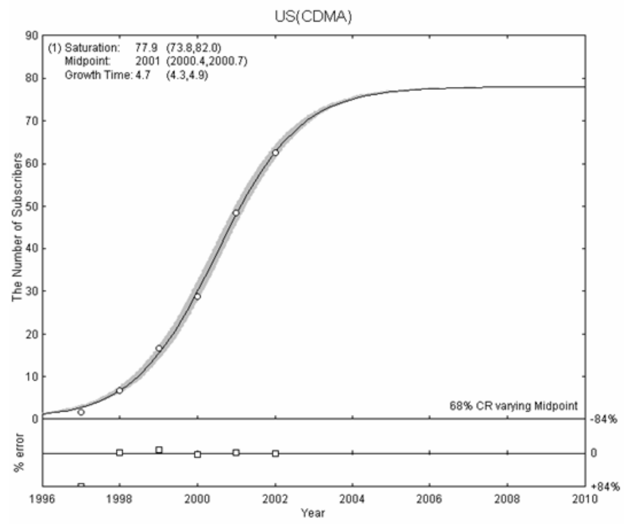
7) US CDMA (95% and 68% CI – varying saturation)



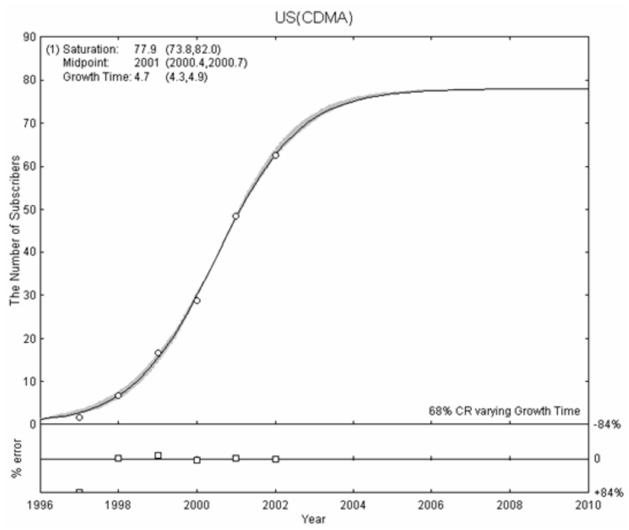


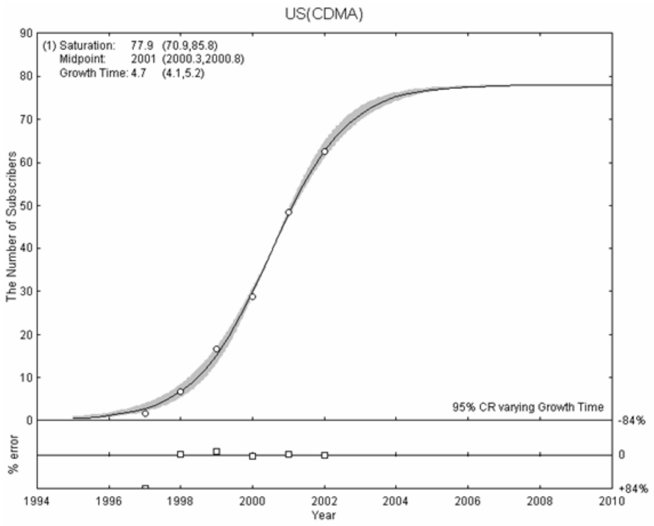
8) US CDMA (95% and 68% CI – varying midpoint)



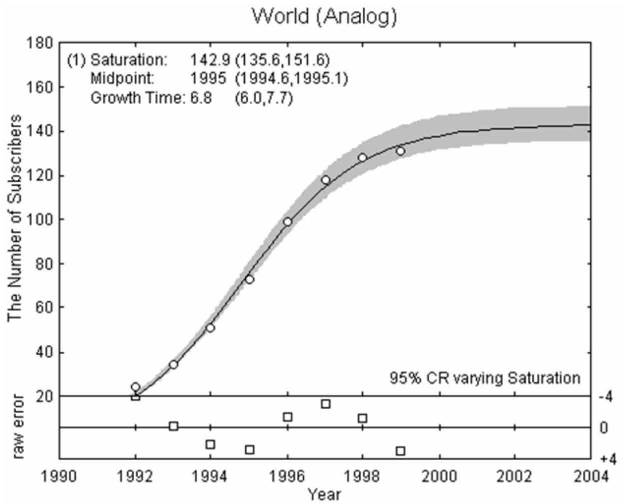


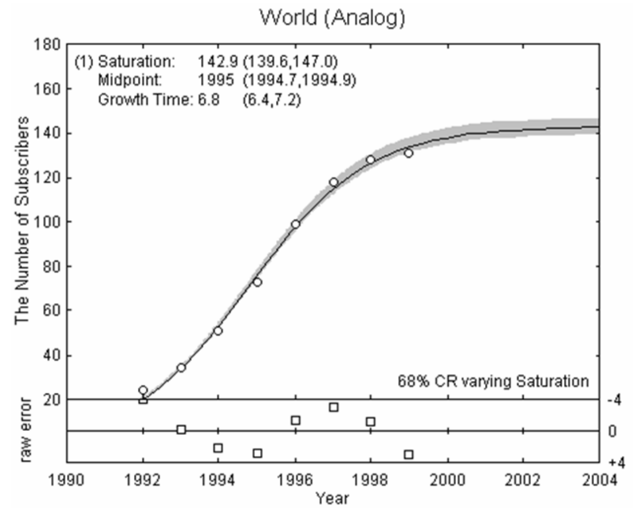
9) US CDMA (95% and 68% CI – varying growth time)



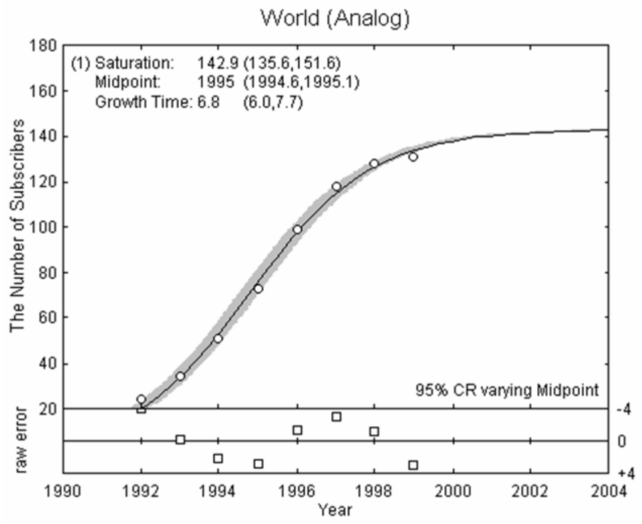


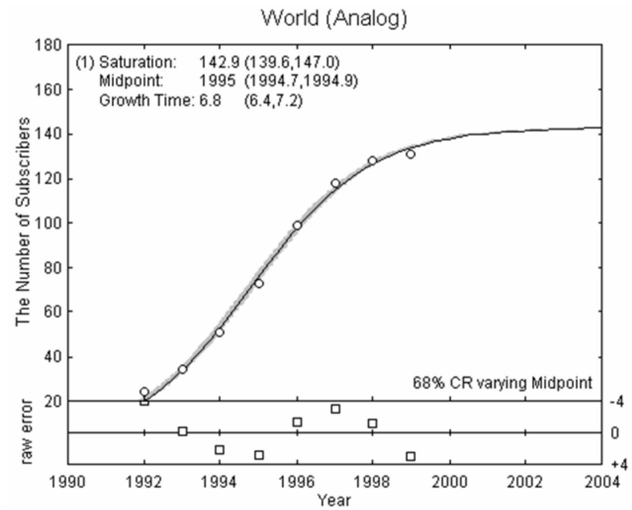
10) World Analog (95% and 68% CI – varying saturation)



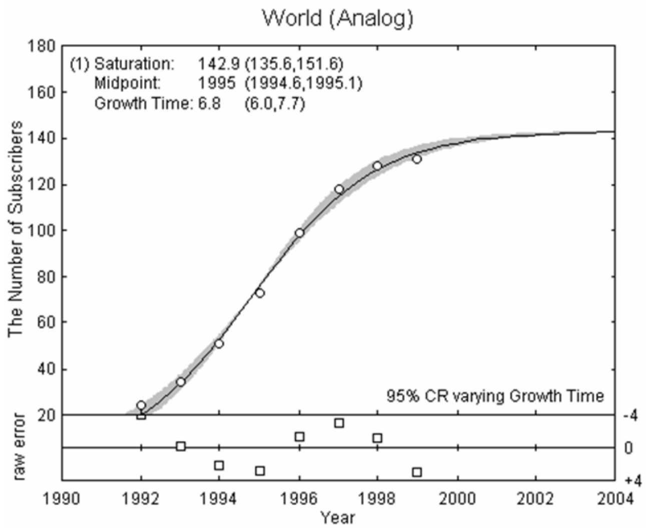


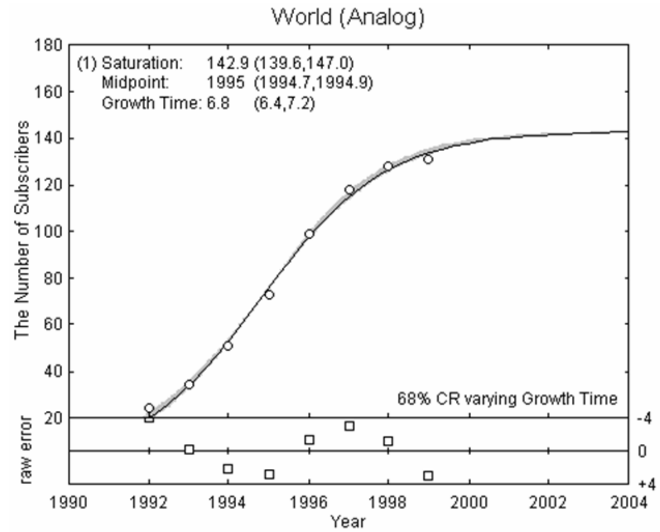
11) World Analog (95% and 68% CI – varying midpoint)



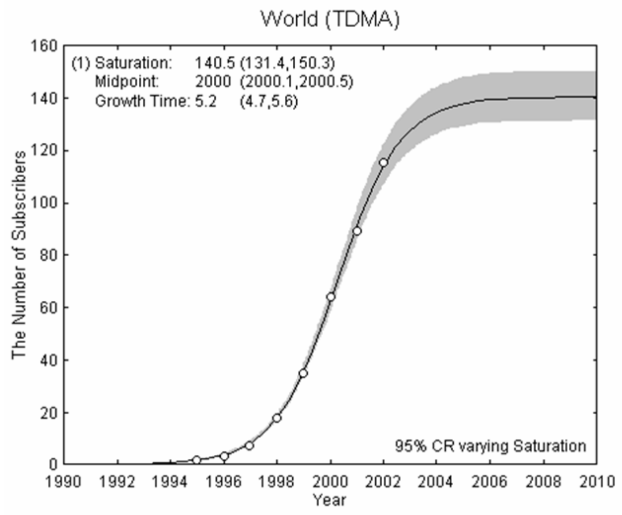


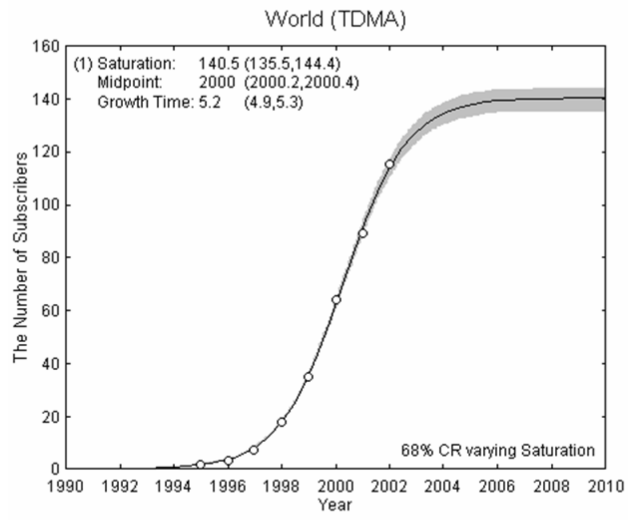
12) World Analog (95% and 68% CI – varying growth time)



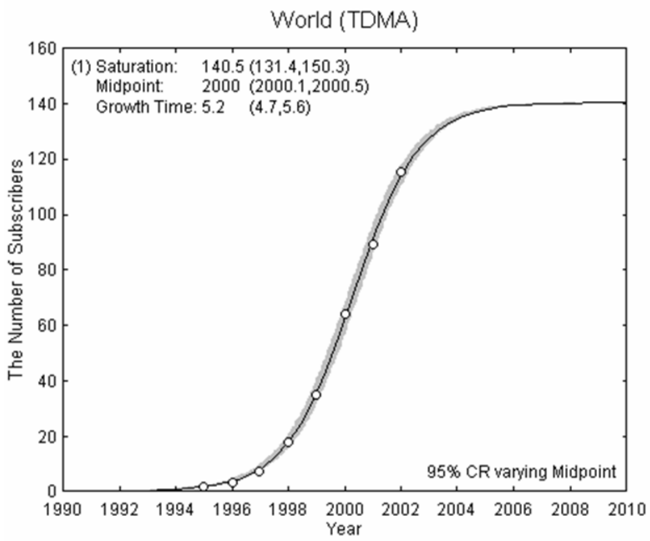


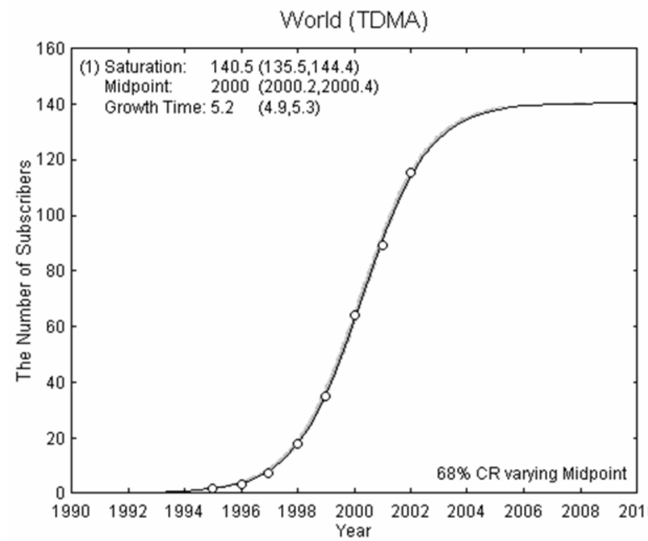
13) World TDMA (95% and 68% CI – varying saturation)



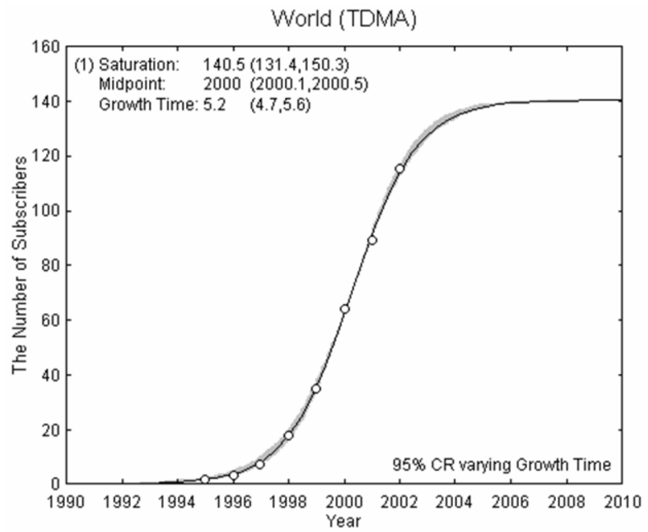


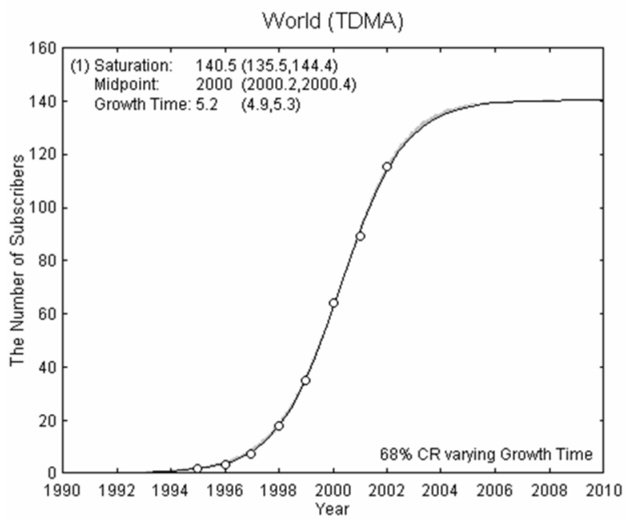
14) World TDMA (95% and 68% CI – varying midpoint)



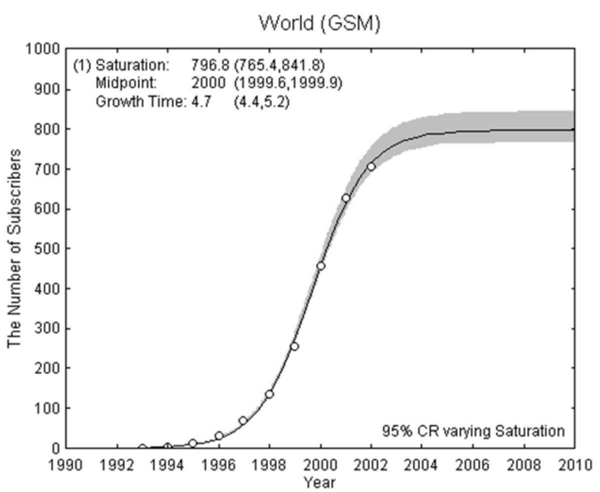


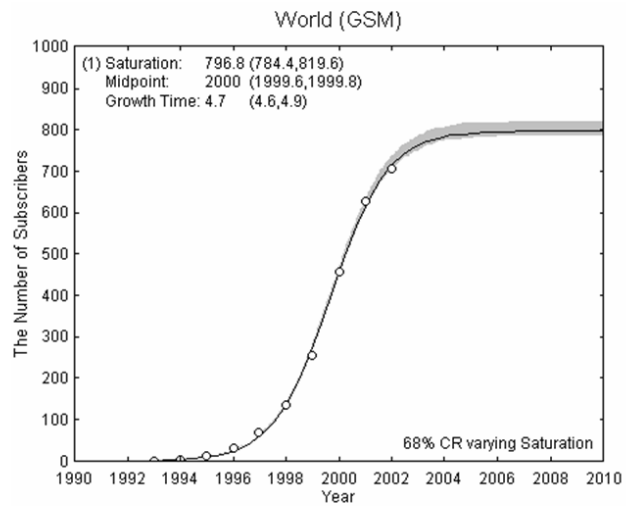
15) World TDMA (95% and 68% CI – varying midpoint)



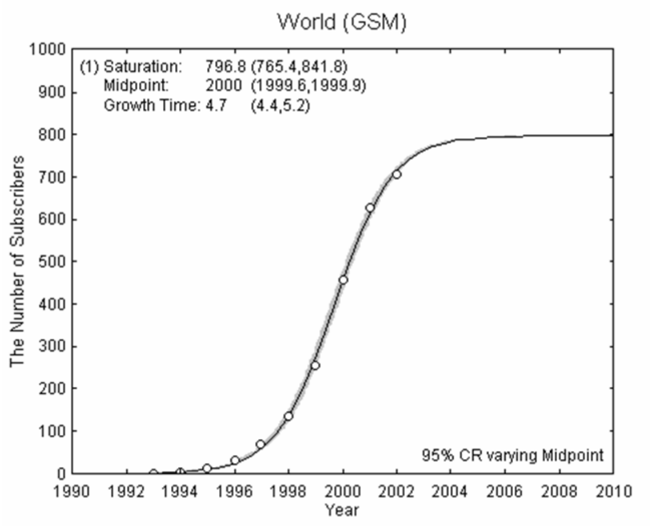


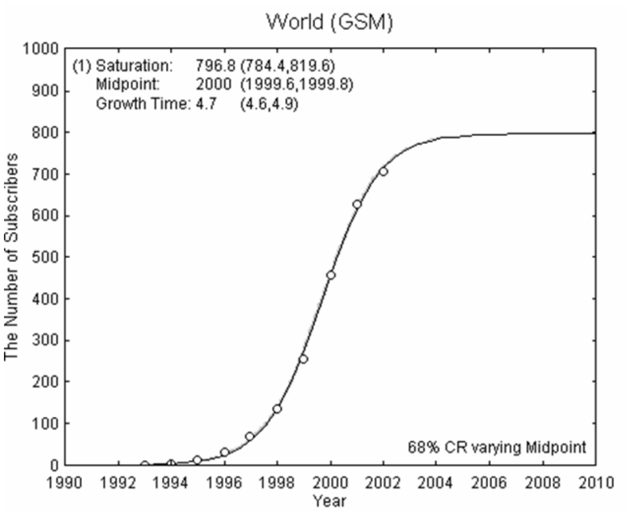
16) World GSM (95% and 68% CI – varying saturation)



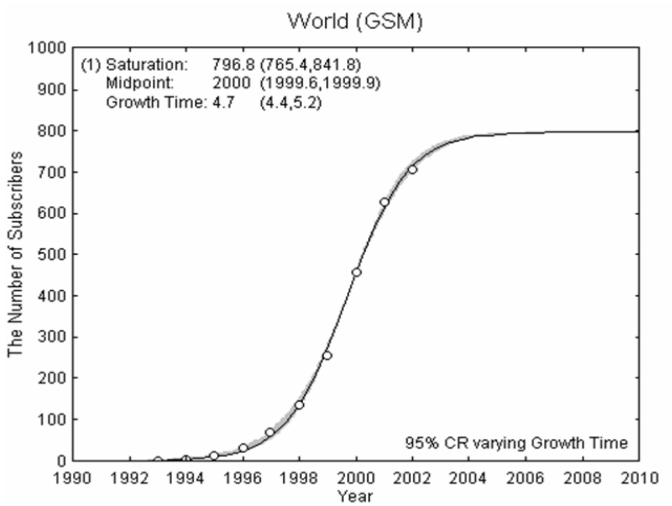


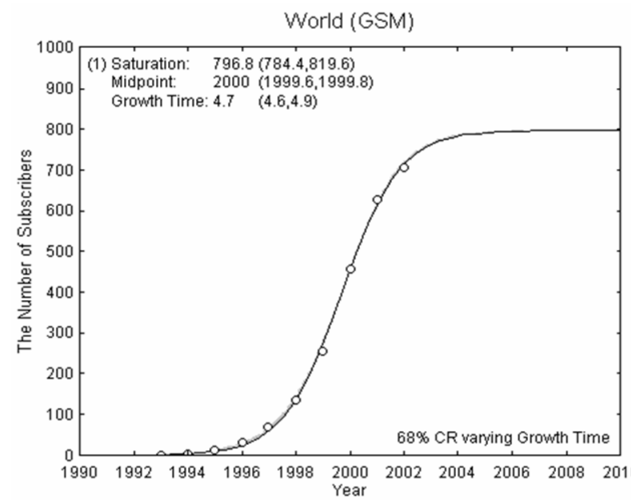
17) World GSM (95% and 68% CI – varying midpoint)



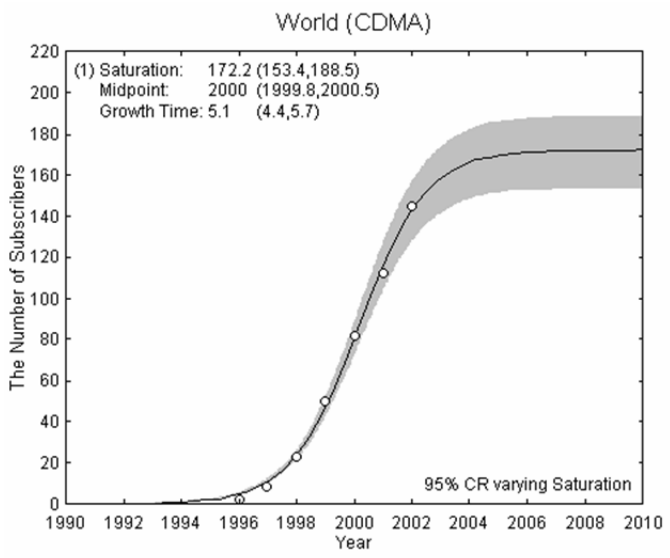


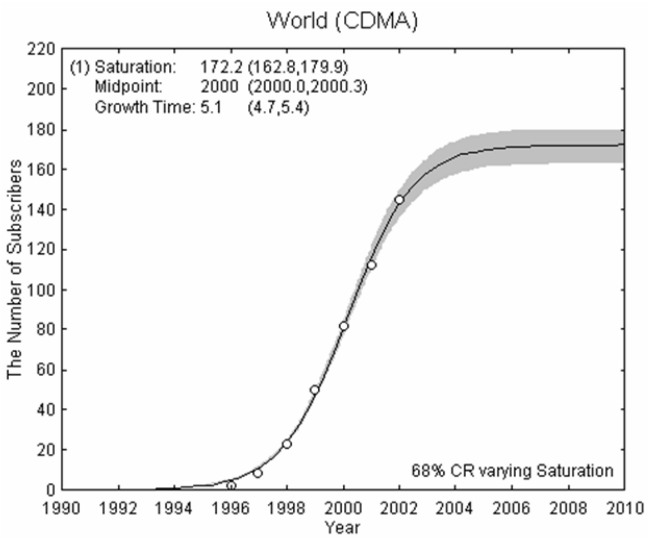
18) World GSM (95% and 68% CI – varying midpoint)



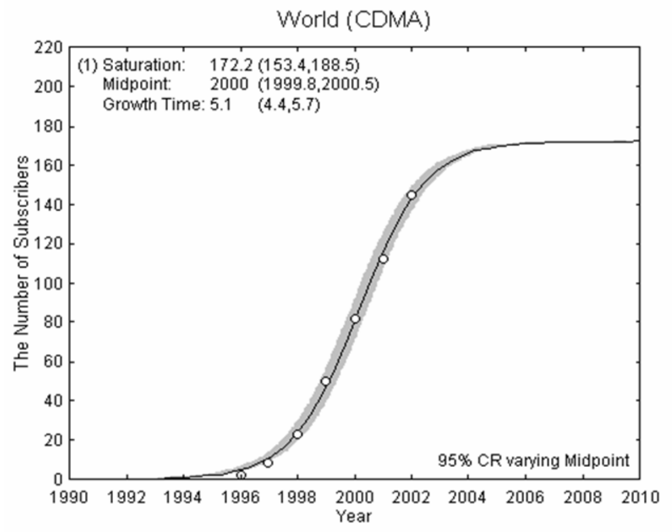


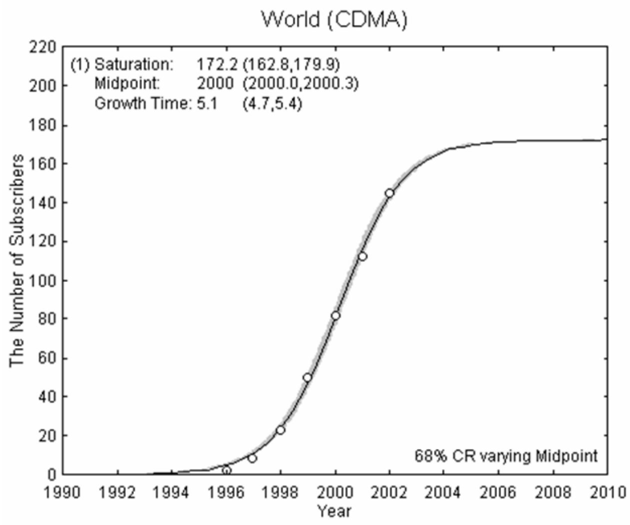
19) World CDMA (95% and 68% CI – varying saturation)



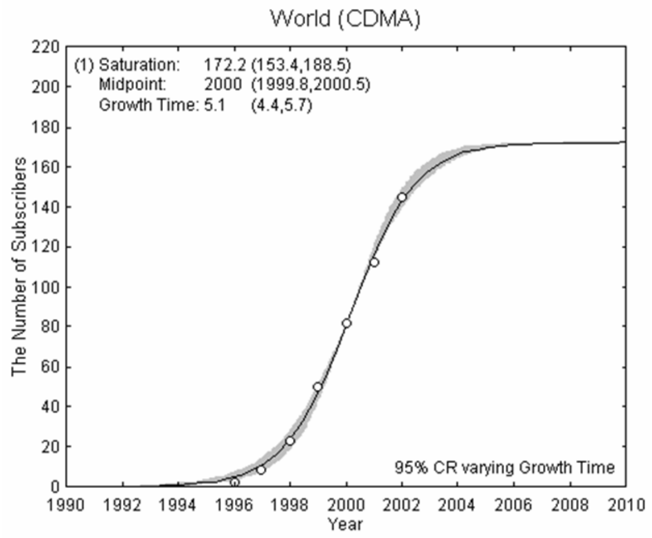


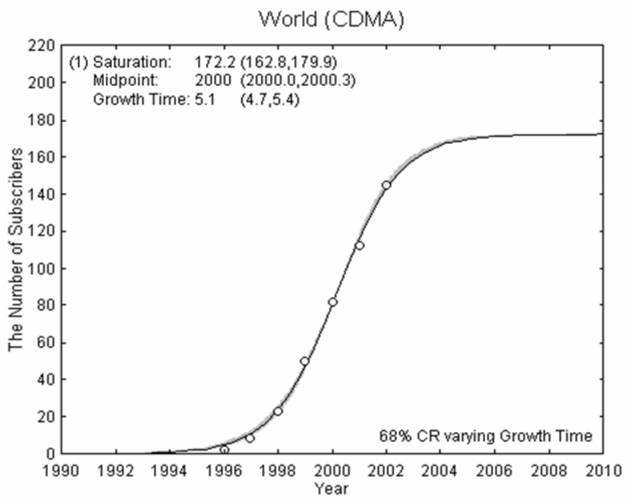
20) World CDMA (95% and 68% CI – varying midpoint)





21) World CDMA (95% and 68% CI – varying midpoint)





22) US Subscribers

(unit: million)

Year	Total	GSM	CDMA	TDMA	Analog
1985	0.34				0.34
1986	0.682				0.682
1987	1.23				1.23
1988	1.609				1.609
1989	3.509				3.509
1990	5.283				5.283
1991	7.557				7.557
1992	11.00				11.00
1993	17.30				17.30
1994	24.00				24.00
1995	34.00			2.00	32.00
1996	44.00			4.00	40.00
1997	55.00		1.50	10.50	43.00
1998	69.00		6.80	17.20	45.00
1999	86.00		16.50	28.50	41.00
2000	109.00	10.00	28.70	39.30	31.00
2001	128.00	14.00	48.42	41.58	24.00
2002	141.00	18.00	62.50	50.39	10.11

23) World Subscribers

(unit: million)

Year	Total	GSM	CDMA	TDMA	Analog
1992	24	0	0	0	24
1993	35	1	0	0	34
1994	56	5	0	0	51
1995	88	13	0	2	73
1996	136	33	2	3	99
1997	204	71	8	7	118
1998	307	138	23	18	128
1999	474	258	50	35	131
2000	722	457	82	64	68
2001	934	628	112	89	44
2002	1,027	705	145	115	29

<u>Parameters for Technology Transition Real Option Model</u>

1. World Wireless Industry

(1) Analog and GSM (world)

Year	Analog	GSM	x=B/P	σ	δ	ρ	T	d1	d2
1993	32.57	1.40	0.04	0.0194	0.04	0.93	0.0005	-1.366378	-1.366868
1994	51.02	3.60	0.07	0.0275	0.06	0.93	0.0016	-1.150665	-1.152245
1995	80.95	8.00	0.10	0.0357	0.09	0.93	0.0029	-1.003667	-1.006533
1996	119.50	19.80	0.17	0.0427	0.10	0.93	0.0044	-0.778512	-0.782893
1997	129.20	71.10	0.55	0.0441	0.12	0.93	0.0065	-0.256155	-0.262630
1998	138.87	138.40	1.00	0.0454	0.13	0.93	0.0086	0.002813	-0.005764
1999	130.90	258.00	1.97	0.0465	0.15	0.93	0.0109	0.300117	0.289244
2000	68.00	455.10	6.69	0.0582	0.20	0.93	0.0210	0.836113	0.815083
2001	43.60	666.20	15.28	0.0661	0.17	0.93	0.0114	1.189815	1.178421
2002	29.30	910.20	31.06	0.0733	0.17	0.93	0.0115	1.498008	1.486531

(2) Analog and CDMA (World)

Year	Analog	CDMA	x=B/P	σ	δ	ρ	T	d1	d2
1993	32.57	0.00							
1994	51.02	0.00							
1995	80.95	0.00							
1996	119.50	2.00	0.02	0.0427	0.11	0.00	0.0141	-1.769297	-1.783379
1997	129.20	7.80	0.06	0.0441	0.15	0.00	0.0254	-1.206463	-1.231873
1998	138.87	23.00	0.17	0.0454	0.18	0.00	0.0362	-0.762797	-0.798971
1999	130.90	50.10	0.38	0.0465	0.20	0.00	0.0435	-0.395361	-0.438843
2000	68.00	82.00	1.21	0.0582	0.21	0.00	0.0496	0.106087	0.056522
2001	43.60	112.30	2.58	0.0661	0.22	0.00	0.0538	0.437791	0.383996
2002	29.30	145.40	4.96	0.0733	0.23	0.00	0.0575	0.724462	0.666932

(3) Analog and TDMA (World)

Year	Analog	TDMA	x=B/P	σ	δ	ρ	T	d1	d2
1993	32.57	0.04	0.00	0.0194	0.04	0.87	0.0007	-2.968342	-2.969024
1994	51.02	0.38	0.01	0.0275	0.09	0.87	0.0048	-2.127875	-2.132656
1995	80.95	2.06	0.03	0.0357	0.13	0.87	0.0096	-1.590565	-1.600191
1996	119.50	2.70	0.02	0.0427	0.17	0.87	0.0174	-1.637317	-1.654691
1997	129.20	6.90	0.05	0.0441	0.19	0.87	0.0226	-1.261104	-1.283723
1998	138.87	17.73	0.13	0.0454	0.21	0.87	0.0286	-0.879612	-0.908242
1999	130.90	35.00	0.27	0.0465	0.22	0.87	0.0334	-0.556187	-0.589556
2000	68.00	64.00	0.94	0.0582	0.27	0.87	0.0499	-0.001390	-0.051268
2001	43.60	89.00	2.04	0.0661	0.24	0.87	0.0349	0.327332	0.292475
2002	29.30	115.00	3.92	0.0733	0.25	0.87	0.0348	0.611235	0.576425

(4) TDMA and GSM (World)

Year	TDMA	GSM	x=B/P	σ	δ	ρ	T	d1	d2
1993	0.04	1.40	40.00	0.0413	0.04	0.98	0.0001	1.602088	1.602032
1994	0.38	3.60	9.52	0.0918	0.06	0.98	0.0010	0.979290	0.978331
1995	2.06	8.00	3.89	0.1277	0.09	0.98	0.0022	0.591358	0.589198
1996	2.70	19.80	7.33	0.1674	0.10	0.98	0.0046	0.867587	0.863016
1997	6.90	71.10	10.30	0.1873	0.12	0.98	0.0053	1.015654	1.010387
1998	17.73	138.40	7.81	0.2074	0.13	0.98	0.0064	0.895631	0.889273
1999	35.00	258.00	7.37	0.2218	0.15	0.98	0.0068	0.870931	0.864172
2000	64.00	455.10	7.11	0.2723	0.20	0.98	0.0073	0.855570	0.848284
2001	89.00	666.20	7.49	0.2416	0.17	0.98	0.0071	0.877747	0.870682
2002	115.00	910.20	7.91	0.2471	0.17	0.98	0.0070	0.901940	0.894938

(5) TDMA and CDMA (World)

Year	TDMA	CDMA	x=B/P	σ	δ	ρ	T	d1	d2
1993	0.04	0.00							
1994	0.38	0.00							
1995	2.06	0.00							
1996	2.70	2.00	0.74	0.1674	0.11	0.99	0.0037	-0.128506	-0.132162
1997	6.90	7.80	1.13	0.1873	0.15	0.99	0.0018	0.054170	0.052321
1998	17.73	23.00	1.30	0.2074	0.18	0.99	0.0014	0.113756	0.112331
1999	35.00	50.10	1.43	0.2218	0.20	0.99	0.0014	0.156477	0.155062
2000	64.00	82.00	1.28	0.2723	0.21	0.99	0.0047	0.109977	0.105291
2001	89.00	112.30	1.26	0.2416	0.22	0.99	0.0016	0.101815	0.100165
2002	115.00	145.40	1.26	0.2471	0.23	0.99	0.0017	0.102711	0.101022

(6) GSM and CDMA (World)

Year	GSM	CDMA	x=B/P	σ	δ	ρ	T	d1	d2
1993	1.40	0.00							
1994	3.60	0.00							
1995	8.00	0.00							
1996	19.80	2.00	0.10	0.1040	0.11	0.99	0.0003	-0.995466	-0.995804
1997	71.10	7.80	0.11	0.1198	0.15	0.99	0.0016	-0.958985	-0.960565
1998	138.40	23.00	0.17	0.1333	0.18	0.99	0.0033	-0.777774	-0.781043
1999	258.00	50.10	0.19	0.1460	0.20	0.99	0.0040	-0.709767	-0.713797
2000	455.10	82.00	0.18	0.1975	0.21	0.99	0.0014	-0.743602	-0.744984
2001	666.20	112.30	0.17	0.1654	0.22	0.99	0.0042	-0.771139	-0.775311
2002	910.20	145.40	0.16	0.1718	0.23	0.99	0.0042	-0.794471	-0.798674

2. US Wireless Industry

(1) Analog and GSM (US)

Year	Analog	GSM	x=B/P	σ	δ	ρ	T	d1	d2
1993	1.00	0.00	0.00						
1994	1.00	0.00	0.00						
1995	0.94	0.00	0.00						
1996	0.91	0.00	0.00						
1997	0.78	0.00	0.00						
1998	0.65	0.00	0.00						
1999	0.48	0.00	0.00						
2000	0.28	0.09	0.32						
2001	0.19	0.11	0.58	0.2116	0.15	-0.98	0.1311	-0.168512	-0.299654
2002	0.07	0.13	1.78	0.2376	0.11	-0.98	0.1182	0.309597	0.191445
2003	0.04	0.15	3.57	0.3043	0.14	-0.98	0.1969	0.651139	0.454216
2004	0.02	0.16	6.63	0.2919	0.25	-0.98	0.2891	0.966194	0.677082

(2) Analog and CDMA (US)

Year	Analog	CDMA	x=B/P	σ	δ	ρ	T	d1	d2
1993	1.00	0.00							
1994	1.00	0.00							
1995	0.94	0.00							
1996	0.91	0.00							
1997	0.78	0.03							
1998	0.65	0.10	0.15	0.1211	0.21	-0.99	0.1093	-0.766052	-0.875355
1999	0.48	0.19	0.40	0.1577	0.22	-0.99	0.1419	-0.324365	-0.466235
2000	0.28	0.26	0.93	0.2038	0.20	-0.99	0.1634	0.048234	-0.115194
2001	0.19	0.38	2.02	0.2116	0.21	-0.99	0.1807	0.395149	0.214478
2002	0.07	0.44	6.18	0.2376	0.22	-0.99	0.2056	0.893909	0.688349
2003	0.04	0.48	11.34	0.3043	0.21	-0.99	0.2635	1.186360	0.922831
2004	0.02	0.47	20.16	0.2919	0.36	-0.99	0.4208	1.514843	1.094044

(3) Analog and TDMA (US)

Year	Analog	TDMA	x=B/P	σ	δ	ρ	T	d1	d2
1993	1.00	0.00							
1994	1.00	0.00							
1995	0.94	0.00							
1996	0.91	0.06							
1997	0.78	0.09							
1998	0.65	0.19	0.29	0.1211	0.01	-0.91	0.0158	-0.525633	-0.541441
1999	0.48	0.25	0.52	0.1577	0.22	-0.91	0.1375	-0.212840	-0.350372
2000	0.28	0.33	1.17	0.2038	0.27	-0.91	0.2163	0.174555	-0.041733
2001	0.19	0.36	1.92	0.2116	0.24	-0.91	0.1959	0.381907	0.186023
2002	0.07	0.32	4.53	0.2376	0.25	-0.91	0.2239	0.768107	0.544178
2003	0.04	0.36	8.52	0.3043	0.00	-0.91	0.0926	0.976695	0.884116
2004	0.02	0.33	13.97	0.2919	0.00	-0.91	0.0852	1.187686	1.102469

(4) TDMA and GSM (US)

Year	TDMA	GSM	x=B/P	σ	δ	ρ	T	d1	d2
1993	0.00	0.00							
1994	0.00	0.00							
1995	0.06	0.00							
1996	0.09	0.00							
1997	0.19	0.00							
1998	0.25	0.00							
1999	0.33	0.00							
2000	0.36	0.09							
2001	0.32	0.11	0.34	0.1795	0.15	0.75	0.0144	-0.465570	-0.479942
2002	0.36	0.13	0.36	0.2613	0.11	0.75	0.0376	-0.428295	-0.465849
2003	0.33	0.15	0.46	0.2903	0.14	0.75	0.0426	-0.317360	-0.359925
2004	0.32	0.16	0.49	0.5996	0.25	0.75	0.1973	-0.213896	-0.411202
2005	0.32	0.16	0.51	0.7641	0.23	0.75	0.3745	-0.104615	-0.479130
2006	0.29	0.15	0.52	0.7719	0.32	0.75	0.3250	-0.120277	-0.445260
2007	0.27	0.14	0.53	0.7637	0.40	0.75	0.2853	-0.136276	-0.421564
2008	0.25	0.13	0.53	0.7435	0.40	0.75	0.2677	-0.142064	-0.409813
2009	0.21	0.11	0.53	0.7334	0.40	0.75	0.2570	-0.145951	-0.402963
2010	0.17	0.09	0.53	0.7070	0.38	0.75	0.2395	-0.154719	-0.394195

(5) TDMA and CDMA (US)

Year	TDMA	CDMA	x=B/P	σ	δ	ρ	T	d1	d2
1993	0.00	0.00							
1994	0.00	0.00							
1995	0.06	0.00							
1996	0.09	0.00							
1997	0.19	0.03	0.14						
1998	0.25	0.10	0.40	0.0051	0.21	0.95	0.0423	-0.381888	-0.424151
1999	0.33	0.19	0.58	0.0652	0.22	0.95	0.0254	-0.224664	-0.250058
2000	0.36	0.26	0.73	0.0576	0.20	0.95	0.0219	-0.125548	-0.147473
2001	0.32	0.38	1.16	0.1795	0.21	0.95	0.0051	0.068677	0.063604
2002	0.36	0.44	1.24	0.2613	0.22	0.95	0.0076	0.097332	0.089739
2003	0.33	0.48	1.46	0.2903	0.21	0.95	0.0125	0.169501	0.157050
2004	0.32	0.47	1.48	0.5996	0.36	0.95	0.0795	0.209995	0.130519
2005	0.32	0.47	1.49	0.7641	0.34	0.95	0.2041	0.274452	0.070306
2006	0.29	0.44	1.49	0.7719	0.35	0.95	0.2033	0.274924	0.071578
2007	0.27	0.41	1.49	0.7637	0.37	0.95	0.1837	0.264891	0.081233
2008	0.25	0.37	1.49	0.7435	0.37	0.95	0.1689	0.257587	0.088651
2009	0.21	0.31	1.49	0.7334	0.37	0.95	0.1571	0.251671	0.094545
2010	0.17	0.26	1.49	0.7070	0.36	0.95	0.1453	0.245802	0.100493

(6) GSM and CDMA (US)

Year	GSM	CDMA	x=B/P	σ	δ	ρ	T	d1	d2
1993	0.00	0.00							
1994	0.00	0.00							
1995	0.00	0.00							
1996	0.00	0.00							
1997	0.00	0.03							
1998	0.00	0.10							
1999	0.00	0.19							
2000	0.09	0.26	2.87						
2001	0.11	0.38	3.46	0.1527	0.21	0.97	0.0061	0.541925	0.535869
2002	0.13	0.44	3.47	0.1080	0.22	0.97	0.0135	0.547356	0.533859
2003	0.15	0.48	3.18	0.1419	0.21	0.97	0.0067	0.505283	0.498552
2004	0.16	0.47	3.04	0.2491	0.36	0.97	0.0180	0.491826	0.473786
2005	0.16	0.47	2.91	0.2276	0.34	0.97	0.0184	0.473433	0.455070
2006	0.15	0.44	2.86	0.3244	0.35	0.97	0.0085	0.460259	0.451781
2007	0.14	0.41	2.83	0.3978	0.37	0.97	0.0107	0.457354	0.446610
2008	0.13	0.37	2.81	0.3952	0.37	0.97	0.0106	0.454357	0.443759
2009	0.11	0.31	2.80	0.4010	0.37	0.97	0.0109	0.453013	0.442117
2010	0.09	0.26	2.80	0.3844	0.36	0.97	0.0099	0.452572	0.442637

(7) GSM and WCDMA (US)

Year	GSM	WCDMA	x=B/P	σ	δ	ρ	T	d1	d2
1993	0.00	0.00							
1994	0.00	0.00							
1995	0.00	0.00							
1996	0.00	0.00							
1997	0.00	0.00							
1998	0.00	0.00							
1999	0.00	0.00							
2000	0.09	0.00							
2001	0.11	0.00							
2002	0.13	0.00							
2003	0.15	0.00							
2004	0.16	0.02	0.10	0.2491	0.25	-0.88	0.2317	-0.875492	-1.107150
2005	0.16	0.03	0.16	0.2276	0.19	-0.88	0.1645	-0.701354	-0.865856
2006	0.15	0.06	0.38	0.3244	0.26	1.00	0.0039	-0.423786	-0.427697
2007	0.14	0.09	0.62	0.3978	0.23	-0.97	0.3901	-0.009190	-0.399301
2008	0.13	0.13	0.98	0.3952	0.22	-0.97	0.3737	0.176583	-0.197144
2009	0.11	0.18	1.63	0.4010	0.22	-0.98	0.3884	0.406621	0.018221
2010	0.09	0.24	2.61	0.3844	0.21	-0.98	0.3516	0.592010	0.240401

(8) GSM and cdma2000 (US)

Year	GSM	cdma2000	x=B/P	σ	δ	ρ	T	d1	d2
1993	0.00	0.00							
1994	0.00	0.00							
1995	0.00	0.00							
1996	0.00	0.00							
1997	0.00	0.00							
1998	0.00	0.00							
1999	0.00	0.00							
2000	0.09	0.00							
2001	0.11	0.00							
2002	0.13	0.00							
2003	0.15	0.00							
2004	0.16	0.02	0.10	0.2491	0.25	-0.88	0.2310	-0.877857	-1.108842
2005	0.16	0.03	0.16	0.2276	0.19	-0.88	0.1665	-0.707129	-0.873652
2006	0.15	0.06	0.37	0.3244	0.26	-0.88	0.3263	-0.271583	-0.597927
2007	0.14	0.09	0.61	0.3978	0.23	-0.88	0.3751	-0.027241	-0.402300
2008	0.13	0.12	0.95	0.3952	0.22	-0.88	0.3592	0.157840	-0.201398
2009	0.11	0.18	1.59	0.4010	0.23	-0.88	0.3716	0.386222	0.014575
2010	0.09	0.23	2.54	0.3844	0.21	-0.88	0.3367	0.572596	0.235848

(9) CDMA and WCDMA (US)

Year	CDMA	WCDMA	x=B/P	σ	δ	ρ	T	d1	d2
1993	0.00	0.00							
1994	0.00	0.00							
1995	0.00	0.00							
1996	0.00	0.00							
1997	0.03	0.00							
1998	0.10	0.00							
1999	0.19	0.00							
2000	0.26	0.00							
2001	0.38	0.00							
2002	0.44	0.00							
2003	0.48	0.00							
2004	0.47	0.02	0.03	0.3587	0.25	-0.97	0.3625	-1.292858	-1.655395
2005	0.47	0.03	0.06	0.3421	0.19	-0.97	0.2804	-1.107670	-1.388043
2006	0.44	0.06	0.13	0.3520	0.26	-0.97	0.3721	-0.695736	-1.067787
2007	0.41	0.09	0.22	0.3693	0.23	-0.97	0.3554	-0.478521	-0.833934
2008	0.37	0.13	0.35	0.3670	0.22	-0.97	0.3402	-0.289236	-0.629441
2009	0.31	0.18	0.58	0.3729	0.22	-0.97	0.3528	-0.058721	-0.411567
2010	0.26	0.24	0.93	0.3607	0.21	-0.97	0.3228	0.129998	-0.192795

(10) CDMA and cdma2000 (US)

Year	CDMA	cdma2000	x=B/P	σ	δ	ρ	T	d1	d2
1993	0.00	0.00							
1994	0.00	0.00							
1995	0.00	0.00							
1996	0.00	0.00							
1997	0.03	0.00							
1998	0.10	0.00							
1999	0.19	0.00							
2000	0.26	0.00							
2001	0.38	0.00							
2002	0.44	0.00							
2003	0.48	0.00							
2004	0.47	0.02	0.03	0.3587	0.25	-0.97	0.3617	-1.295299	-1.657011
2005	0.47	0.03	0.06	0.3421	0.19	-0.97	0.2830	-1.113119	-1.396166
2006	0.44	0.06	0.13	0.3520	0.26	-0.97	0.3753	-0.703127	-1.078422
2007	0.41	0.09	0.22	0.3693	0.23	-0.97	0.3576	-0.487943	-0.845563
2008	0.37	0.12	0.34	0.3670	0.22	-0.97	0.3420	-0.299827	-0.641846
2009	0.31	0.18	0.57	0.3729	0.23	-0.97	0.3546	-0.069859	-0.424475
2010	0.26	0.23	0.90	0.3607	0.21	-0.97	0.3246	0.118909	-0.205673

(11) TDMA and WCDMA (US)

Year	TDMA	WCDMA	x=B/P	σ	δ	ρ	T	d1	d2
1993	0.00	0.00							
1994	0.00	0.00							
1995	0.06	0.00							
1996	0.09	0.00							
1997	0.19	0.00							
1998	0.25	0.00							
1999	0.33	0.00							
2000	0.36	0.00							
2001	0.32	0.00							
2002	0.36	0.00							
2003	0.33	0.00							
2004	0.32	0.02	0.05	0.5996	0.25	-0.98	0.7122	-0.947792	-1.659947
2005	0.32	0.03	0.08	0.7641	0.19	-0.98	0.9065	-0.622209	-1.528746
2006	0.29	0.06	0.20	0.7719	0.26	-0.98	1.0617	-0.177654	-1.239367
2007	0.27	0.09	0.33	0.7637	0.23	-0.98	0.9826	0.008135	-0.974466
2008	0.25	0.13	0.52	0.7435	0.22	-0.98	0.9225	0.175031	-0.747471
2009	0.21	0.18	0.87	0.7334	0.22	-0.98	0.9123	0.394096	-0.518168
2010	0.17	0.24	1.39	0.7070	0.21	-0.98	0.8375	0.560482	-0.276984

(12) TDMA and cdma2000 (US)

Year	TDMA	cdma2000	x=B/P	σ	δ	ρ	T	d1	d2
1993	0.00	0.00							
1994	0.00	0.00							
1995	0.06	0.00							
1996	0.09	0.00							
1997	0.19	0.00							
1998	0.25	0.00							
1999	0.33	0.00							
2000	0.36	0.00							
2001	0.32	0.00							
2002	0.36	0.00							
2003	0.33	0.00							
2004	0.32	0.02	0.05	0.5996	0.25	-0.98	0.7110	-0.950396	-1.661400
2005	0.32	0.03	0.08	0.7641	0.19	-0.98	0.9113	-0.626592	-1.537934
2006	0.29	0.06	0.19	0.7719	0.26	-0.98	1.0672	-0.183932	-1.251115
2007	0.27	0.09	0.32	0.7637	0.23	-0.98	0.9863	-0.000556	-0.986825
2008	0.25	0.12	0.50	0.7435	0.22	-0.98	0.9255	0.165027	-0.760463
2009	0.21	0.18	0.84	0.7334	0.23	-0.98	0.9151	0.383498	-0.531615
2010	0.17	0.23	1.35	0.7070	0.21	-0.98	0.8404	0.549941	-0.290410

(13) TDMA/GSM and WCDMA (US)

Year	TDMA/GSM	WCDMA	x=B/P	σ	δ	ρ	T	d1	d2
1993	0.00	0.00							
1994	0.00	0.00							
1995	0.00	0.00							
1996	0.06	0.00							
1997	0.09	0.00							
1998	0.19	0.00							
1999	0.25	0.00							
2000	0.33	0.00							
2001	0.45	0.00							
2002	0.43	0.00							
2003	0.49	0.00							
2004	0.48	0.02	0.03	0.3548	0.25	0.36	0.1126	-1.422365	-1.534981
2005	0.47	0.03	0.06	0.3590	0.18	0.36	0.1301	-1.186173	-1.316309
2006	0.48	0.06	0.12	0.3495	0.26	0.36	0.1340	-0.851706	-0.985685
2007	0.45	0.09	0.20	0.3735	0.29	0.36	0.3391	-0.528646	-0.867727
2008	0.42	0.13	0.31	0.3742	0.60	0.36	0.5197	-0.252320	-0.771990
2009	0.38	0.18	0.48	0.3815	0.76	0.36	0.5310	-0.049703	-0.580672
2010	0.32	0.24	0.74	0.3711	0.77	0.36	0.1377	-0.059627	-0.197340

(14) TDMA/GSM and cdma2000 (US)

Year	TDMA/GSM	cdma2000	x=B/P	σ	δ	ρ	T	d1	d2
1993	0.00	0.00							
1994	0.00	0.00							
1995	0.00	0.00							
1996	0.06	0.00							
1997	0.09	0.00							
1998	0.19	0.00							
1999	0.25	0.00							
2000	0.33	0.00							
2001	0.45	0.00							
2002	0.43	0.00							
2003	0.49	0.00							
2004	0.48	0.02	0.03	0.3548	0.25	0.36	0.1141	-1.423661	-1.537742
2005	0.47	0.03	0.06	0.3590	0.19	0.36	0.1308	-1.192630	-1.323425
2006	0.48	0.06	0.12	0.3495	0.26	0.36	0.1180	-0.868724	-0.986693
2007	0.45	0.09	0.20	0.3735	0.23	0.36	0.1292	-0.644090	-0.773333
2008	0.42	0.12	0.30	0.3742	0.22	0.36	0.1305	-0.458393	-0.588914
2009	0.38	0.18	0.47	0.3815	0.23	0.36	0.1326	-0.260926	-0.393495
2010	0.32	0.23	0.72	0.3711	0.21	0.36	0.1377	-0.071611	-0.209324

BIBLIOGRAPHY

Amram, M., and N. Kulatilaka (1999). Options: Managing Strategic Investment in an Uncertain World. Boston, Harvard Business School Press.

Anderson, D. M. a. J. B., Pine (1996). Agile Product Devevelopment for Mass Customizatiom: How to Develop and Deliver Products for Mass Customization, Niche Markets, JIT, Build-To-Order and Flexible Manufacturing, McGraw Hill.

Arthur, W. (1989). "Competing Technologies, Increasing Returns, and Lock-in by Historical Events." Economic Journal **99**: PP. 116-131.

Benaroch, M., and Robert J. Kauffman (1998). "A Case for using Real Options Pricing Analysis to Evaluate Information Technology Project Investments." Information System Research.

Bloom, N., and J. Van Reenen (2002). "Patents, real options and firm performance." Economic Journal **112**(478): C97-C116.

Brennan, M. J., and Eduardo S. Schwartz (1985). "Evaluating Natural Resources Investments." Journal of Business **58**: PP. 135-157.

Brigham, E., et al. (1998). Financial Management: Theory and Practice (9th edition), Dryden Press.

Buchannan, K., , et al. (1997). "IMT-2000: Service Provider's Perspective." IEEE Communication Magazine: PP. 8-13.

Budde, P. (2003). USA-Wireless Communications. Telecommunications and Information Highways, Paul Budde Communications Pty Ltd.

Capozza, D., and Y. Li. (1994). "The Intensity and timing of Investment: The case of land." American Economic Review **84**(4): PP. 889-904.

Carr, P. (1988). "The Valuation of sequential exchange opportunities." Journal of Finance **43**(5): PP. 1235-1256.

Carsello, R. e. a. (1997). "IMT-2000 Standards: Radio Aspects." IEEE Personal Communications: PP. 30-40.

Chris, N. (1997). Black-Scholes and Beyond Option Pricing Models, Irwin Publishing.

Cox, J., et al. (1979). "Option Pricing: A Simplified Approach." Journal of Financial Economics: PP. 229-264.

CTIA (2003). CTIA's Semi--Annual Wireless Industry Survey, Cellular Telecommunications & Internet Association.

Dahlman, E. e. a. (1998). "UMTS/IMT-2000 Based on Wideband CDMA." IEEE Communication Magazine: PP. 70-80.

Dalal, N. (2002). A Comparative Study of UMTS (WCDMA) and cdma2000 Networks, Award Solutions, Inc.

Deng, S., Blake Johnson, and Aram Sogomonian (1998). Exotic Electricity Options and the Valuation of Electricity Generation and Transmission Assets.

Dias, M. A. G. a. K. M. C. R. (1999). Petroleum Concessions with Extendible Options using Mean Reversion with Jumps to Model oil Prices. the 3rd International Conference on Real Options, the Netherlands.

Dixit, A. K., and R.S. Pindyck (1994). Investment under Uncertainty, Princeton University Press.

Dosi, G. (1982). "Technological paradigms & technological trajectories." Research Policy **11**: PP. 147-162.

Dravida, S., Jiang, H., Kodialam, M., Samadi, B. and Wang, Y. (1998). "Narrowband and Broadband Infrastructure Design for Wireless Networks." IEEE Communication Magazine: PP. 72-78.

EMC (2004). World Cellular Review, EMC.

Flatto, J. (1996). Using Real Options in Project Evaluation, Life Office Management Association (LOMA).

Garg, V. (2001). Wireless Network Evolution: 2G to 3G, Prentice Hall.

Gartner (2003). Market View: Quartly Statistics 2003, Gartner Dataquest.

Grubler, A. (1990). The Rise and Fall of Infrastructures. New York, Springer-Verlag.

GSM (2003). Wireless Business Review, GSM Association.

Henderson, R., and K. Clark (1990). "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms." Administrative Science Quarterly **35**: PP. 9-31.

IEC (2003). Wireless Network Technology Tutorials, International Engineering Consortium.

Ingersoll, J., and S. Ross. (1992). "Waiting to Invest: investment and uncertainty." Journal of Business **65**(1): PP. 1-29.

Kellogg, D., John M. Charnes and Riza Demirer (1999). Valuation of a Biotechnology Firm: An Application of Real-Options Methodologie. The 3rd Annual International Conference on Real Options.

Kemma, A. G. Z. (1993). "Case Studies on Real Options." Financial Management **19**(3): PP. 259-270.

Kensinger (1987). "Adding the value of active management into the capital budgeting equation." Midland Corporate Finance Journal **5**(1): PP. 31-42.

Kester, W. (1984). "Today's options for tomorrow's growth." Harvard Business Review **62**(2): PP. 153-160.

Kolbe, A., et al. (1991). "When choosing R&D projects, go with long shots." Research Technology Management: PP. 35-40.

Kulatilaka, N., and A. Marcus (1988). "A general formulation of corporate real options." Research in Finance **7**: PP. 183-200.

Langlois, N. a. R., P. (1992). "Networks and innovation in a modular system: Lessons from the microcomputer and stereo component industries." Research policy **21**(4): PP. 297-313.

Levitas, E., and T. Chi (2001). A real option perspective on the market valuation of a firm's technological competence. Academy of Management, Seattle.

Liebowitz, S., and S. Margolis (1995). "Path Dependence, Lock-In and History." Journal of Law, Economics and Organization.

Maid, S., and R. Pindyck (1987). "Time to build, option value, and investment decisions." Journal of Finance **18**(1): PP. 7-27.

Marchetti, C. (1980). "Society as a learning system." Technological Forecasting and Social Change **18**: PP.267-282.

Marchetti, C., and N. Nakicenovic (1995). The Dynamics of Energy Systems and the Logistic

Substitution Model,. Research Report RR-79-13. Luxenburg, Australia, IIASA.

Margrabe, W. (1978). "The value of an option to exchange one asset for another." Journal of Finance **33**(1): PP. 177-186.

Mason, S., and C. Baldwin (1988). "Evaluation of government subsidies to large-scale energy projects: A contingent claims approach." Advances in Futures and Options Research **3**: PP. 169-181.

McDonald, R., and D. Siegel (1985). "Investment and the valuation of firms when there is an option to shut down." International Economic Review **26**(2): PP. 331-349.

McDonald, R., and D. Siegel (1986). "The value of waiting to invest." Quarterly Journal of Economics **101**: PP. 707-727.

McDysan, D. (2000). Multiservice Networking using a Component-based Switch & Router Architecture.

MDA (2003). The Year Ahead, Mobile Data Association.

Meyer, P., Yung, J., and J. Ausubel (1999). "A Primer on Logistic Growth and Substitution: The Mathematics of the Loglet Software." Technological Forecasting and Social Change **61**(3): PP. 247-271.

Meyer, P. S. (1994). "Bi-logistic growth." Technological Forecasting and Social Change **47**: PP.89-102.

Micalizzi, A. (1996). Plough Case: Valuing Pharmaceutical Development and Expansion Options, Bocconi University.

Myers, S., and S. Maid (1990). "Abandonment value and project life." Advances in Futures and Options Research **4**: PP. 1-21.

Nakicenovic, C. M. a. N. (1979). dynamics of energy systems and the logistic substitution model. Laxenburg, Austria, International Institute for Applied Systems Analysis**:** Research Report RR-79-13.

Ofori, G. (1991). "Programmes for Improving the Performance of Contracting Firms in Developing Countries: A Review of the Approaches and Appropriate Options." onstruction Management and Economics **9**: PP. 19-38.

Paddock, J. L. D. R. S. J. L. S. (1988). "Option Valuation of Claims on Real Assets: The Case of Offshore Petroleum Leases." Quarterly Journal of Economics: PP. 479-508.

Pickles, E. a. J. L. S. (1993). "Petroleum Property Valuation: A Binomial Lattice Implementation of Option Pricing Theory." the Energy Journal **14**(2): PP. 1-26.

Pindyck, R. S. (1988). "Irreversible Investment, Capacity Choice, and the Value of the Firm." American Economic Review **2**: PP. 969-985.

Pine, B. J. (1993). Mass Customization: The New Frontier in Business Competition, Harvard Business School Press.

Pine, B. J. a. J. H., Gilmore (2000). Markets of One: Creating Customer-Unique Value through Mass Customization, A Harvard Business Review Book.

Prasad, R. (1998). "An Overview of CDMA Evolution toward Wideband CDMA." IEEE Communication Surveys **1**(1): PP. 1-29.

Pry, F. a. (1971). "A simple substitution model of technological change." Technological Forecasting and Social Change **3**: PP. 75-88.

Rapport, T. (1996). Wireless Communications Principles and Practice, Prentice-Hall, Inc.

Rubash, K. (1999). A Study of Option Pricing Models, Bradley University.

Sahlman, W. (1988). "Aspects of financial contracting in venture capital." Journal of Applied Corporate Finance **1**: PP. 23-36.

Sanchez, R. (1995). "Strategic flexibility in product competition." Strategic Management Journal **16**: pp. 135-159.

Sanchez, R. (1999). "Modular Architectures in the Marketing Process." Journal of Marketing: PP. 92-111.

Schilling, M. (2000). "Toward a general modular systems theory and its application." Academy of Management Review **25**(2): PP. 312-334.

Shapiro, C., and H. Varian (1999). Information Rule: A Strategic Guide to the Network Economy. Boston, Harvard Business School Press.

Standard&Poor's (2003). Industry Surveys: Telecommunications (Wireless), Standards & Poor's.

Stiller, B. (1997). QoS Methods for Managing Communication Requirements of Distributed Applications.

Stonier, J. (1999). Airbus: Valuing Options in the Airline Industry, University of Maryland.

StrategyAnalytics (2003). Strategy Analytics Global Wireless Practice, Strategy Analytics.

Tibshirani, B. E. a. R. J. (1993). An Introduction to the Bootstrap. New York, Chapman and Hall.

Titman, S. (1985). "Urban Land Prices under Uncertainty." American Economic Review **75**(3): PP. 505-514.

Tourinho, O. (1979). The Option Value of Reserves of Natural Resources. Working Paper, University of California at Berkeley.

Trigeorgis, L. (1993). "The nature of option interactions and the valuation of investments with multiple real options." Journal of financial and Quantitative Analysis **28**(1): PP. 1-20.

Trigeorgis, L. (1996). Real Options Managerial Flexibility and Strategy in Resource Allocation, The MIT Press.

Trigeorgis, L. (1996). Real Options: Managerial Flexibility and Strategy in Resource Allocation, The MIT Press.

Trigeorgis, L., and S. Mason (1987). "Valuing managerial flexibility." Midland Corporate Finance Journal **5**(1): PP. 14-21.

Tseng, C., and G. Barz (1999). Power Plant Operations and Real Options. Real Options and Energy Management - Using Options Methodology to Enhance Capital Budgeting Decisions. E. Ronn.

UMTS (2002). The UMTS 3G Market Forecasts, UMTS Forum.

Venezia, I., and M. Brenner (1979). "The optimal duration of growth investments and search." Journal of Business **52**(3): PP. 393-407.

Vriendt, J., et al. (2002). "Mobile Network Evolution: A Revolution on the Move." IEEE Communication Magazine: PP.104-111.

Williams, J. (1991). "Real Estate Development as an Option." Journal of Real Estate Finance and Economics **4**(2): PP. 191-208.

Wilner, R. (1995). "Valuing: staff-up venture growth option." Journal of Real Estate Finance and Economics **4**(2): PP. 191-208.