Real Options: The Value of Strategic Technology Options in Wireless Industry ¹

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ABSTRACT

The 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. At present, there are many alternative wireless network technologies, such as TDMA, GSM, cdmaOne, GPRS, EDGE, WCDMA, and cdma2000. These wireless technology choices require close examination when making the strategic decisions involving network evolution. So, each wireless service provider must choose a particular transition strategy, indicating when, how, and at what pace to introduce new technologies.

The goal of this project is to support wireless firms' strategic decisions: to migrate or not, if so, which network migration path to take. This research will develop a model to show how technology options migrating into new technology from old technology affect on the value of networks. We also will apply it to assess the value of technology migration options in the US wireless industry. 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.

1. Introduction

1.1 Background

The wireless industry is currently undergoing a major transition from second generation (2G) to third generation (3G) wireless technologies, which offer high speed data services. (Garg, 2001; Dalal, 2002) These high quality data services are the foundation of multimedia and interactive information systems that service providers hope will be a significant contributor to future profits. To that end, equipment providers have been developing the 3G technologies to support these services. (Rappaport, 1996) For their part, the wireless network operators must decide how to migrate their network, i.e., how to best deliver high-quality multimedia services at minimum cost over a smooth evolutionary path. Since the complete replacement of the existing wireless network architecture is generally not practical and since there is an economic trade-off involved in the choice of different technologies, the migration of the existing networks is challenging to network service providers: that is, which migration path to take and what to do once there.

The US wireless market is one of the largest mobile markets in the world, with an estimated 169 million cellular subscribers in December 2004 (CTIA, 2005), nearly one mobile unit for every two Americans. At present, there are three major competing digital standards *CDMA*, *TDMA*, and *GSM*. By mid-1999, 52.5% of wireless market subscribers use analog technology (CTIA, 2005). The reason is that the analog network still has the best geographic coverage in the US. The US wireless industry is constantly evolving, and it has become more competitive since the formation of a number of large providers, like the merger of Cingular and AT&T Wireless.

The US wireless industry now has five nationwide wireless service providers: Cingular-AT&T Wireless, Verizon Wireless, Sprint PCS, T-Wireless, 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 1. Verizon Wireless uses AMPS and *CDMA*; and Cingular-AT&T Wireless use AMPS, *TDMA*, and *GSM*. Sprint Wireless and T-Mobile use *CDMA* and *GSM*, respectively.

	Verizon	Cingular- AT&T	Sprint	T-Mobile	Nextel
AMPS	0	0			iDEN
TDMA		0			(integrated
GSM		0		0	Digital Enhanced Network)
CDMA	0		0		

Table1: US Wireless Firms' Technologies

1.2 Research Motivation and Goal

The fundamental importance of *Real Options* has been recognized in academics and in actual practice as a strategic tool to manage uncertainty (McDonald, 1996; Pindyck, 1988; Sick, 1989; Dixit, 1994; Smith, 1995; Trigeorgis, 1996; Amram,1999). 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 study proposes a theory to show how managing technology and strategies affect the value of wireless networks using the real options approach (ROA). The model is developed to show explicitly the value of technological flexibility (i.e., technology choice) on a firm's strategy in the wireless industry.

The traditional ROAs have typically focused on the issues concerning business investment decisions, such as mining (Brennan, 1985), oil (Dias, 1999; Paddock,1988), medicine R&D (Micalizzi, 1996), and other investment activities (Flatto, 1996; Benaroch, 1998; Deng, 1998; Kellog, 1999; Kemma, 1993; Stonier, 1999). However, this study directly

approaches technology itself to assess its value, especially wireless network technologies (e.g., AMPS, *GSM*, *CDMA*, *WCDMA*, *cdma2000*, etc.).

As the technological uncertainty (Dosi, 1982) in wireless network industry increases, technological flexibility (Trigeogris, 1996; Levitas & Chi, 2001); Bloom & Van Reenen, 2002) is necessary for network service providers to gain competitive advantage. As a result, technological flexibility has recently received some attention in the network industry. However, its potential value still remains uncertain, and the emphasis on technological flexibility is only loosely related to the goal of creating value in the existing network architectures. So, we need better explanatory models for the nature and value of technological flexibility in networks.

Since the complete replacement of the existing wireless network architecture ('green theory) 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, i.e., 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?

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. This study also investigates strategic options of the network migration path as assessed as a way to manage the evolution of wireless network architecture based on ROA.

This paper explores two typical network migration alternatives: the 'Global Systems for Mobile Communications (GSM)-based' network migration path and the 'Code Division Multiple Access (CDMA)-based' network migration path, as strategic options for facilitating the migration into a next generation network architecture. One calls for substantial infrastructure replacement, while the other calls for upgrades to existing equipment towards 3G. However, in this study, we blend a comparative study and a 'what if' study (or contingency study) by considering any possible migration scenarios, using the real options approach (ROA).

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

1.3 Research Issues

The evolutionary paths to 3G from the principal 2G technologies, GSM and CDMA are quite distinct and there are many alternative wireless network technologies, such as TDMA, GSM, GPRS, EDGE, WCDMA, cdma2000, etc. (Prasad, 1998; Garg, 2001; Dalal, 2002; Carsello, 1997; Dahlman, 1998; Dravida, 1998; Rapport, 1996). These abundant choices of wireless technologies require service providers to examine the options for their network evolution as a strategic decision. The main approach of this research, the Real Options Approach (ROA), introduces a new perspective on technology policy issues in networks, such as network architecture and technology choice, network service provisioning, and network regulation and policy. Based on ROA, wireless network operators may find it worthwhile to evaluate new technologies as strategic options. This study intends to raise core issues concerning the transition to 3G and to resolve these both qualitatively and quantitatively.

The 3G wireless market can be broken down into three types of customer groups and three types of service provider groups. In the customer groups, 1) First group is new customers who have never used wireless services, 2) Second group is customers who move from their current *1G* services, and 3) Third group is customers who move from their current *2G* services. In the service provider groups, 1) Firm A-type group is the existing hybrid service providers offering *1G* and *2G* technologies, like Verizon and Cingular-AT&T Wireless. 2) Firm B-type group is the existing service providers only offering *2G* services, like Sprint PCS and T-Mobile, and Nextel And C) finally Firm C-type group is the potential new service providers only offering *3G* services, i.e., *WCDMA* and *cdma2000*.

Based on these simplified market structure, my research issues are two-fold. First, 'what is each firm's migration strategy for 3G' including what technology, when, and how to migrate, and second is how to assess the value of technology migration as a basis of technology migration strategy?



Figure 1: Research Issues

2. Real Options Theories: A Brief Overview

The field of real options has been recognized the fundamental importance in academics and in actual practice as a strategic tool to evaluate business projects investment. (Carr, 1988; Dixit & Pindyck, 1994; Smith & Triantis, 1995; Trigeorgis, 1996) The theory of real options provides a rigorous framework to analyze the optimal exercise of options.

The real options theory is emerged from the criticism of traditional approaches, such as net present value (NPV) analysis. The traditional NPV method is called a *now-or-never* decision rule (Trigeorgis, 1996). However, this simple rule is not appropriate for most investment projects. In reality, the decision for investment can be contingent on what kind of future unfolds. For instance a manager can wait for a time until market situation is improved, or decide not to invest if the market situation is bad, because less uncertainty about the investment.

Options (Trigeorgis, 1996; Dixit & Pindyck, 1994) are simply defined *the right, but not the obligation*, to buy or sell financial assets (stocks/bonds), or real assets (projects and business): the former are financial options and the latter are real options. Black-Scholes and Merton (1973) have defined the options paradigm and have offered some valuation tools. Their assumptions are that trading and decision making take place in continuous time and that the underlying sources of uncertainty follow 'Brownian motions (random walk)'.

Brennan and Schwartz (1985) and McDonald and Siegel (1986) were the first to actually employ these insights in the valuation of real assets, thus helping to complete in the development of project valuation, which has become known as *real options*. After following them, Dixit and Pindyck (1994), Smith (1995), and Trigeorgis (1996) deal with the issue of the timing of investment when there is competition in the product market. Dixit & Pindyck (1994) defined real options as opportunities to respond to changing circumstance of a project by management. These opportunities to change are rights, but not obligations to take some action in the future. The basic idea of real options is the logic for the ability to provide access to significant upside potential while containing downside losses makes options more valuable with greater volatility.

The term "real options" recognizes both the similarities and the differences to financial options. Originally, the concept of real options is analogous to that of financial option, which conveys a right but not an obligation. However, real options differ from financial options in several important respects. First, real options are differentiated from financial options because they involve real assets rather than financial assets. Second, they can not be valued the same way because they are typically less liquid and the real value of an investment to one firm may differ significantly from its value to another firm. This creates a substantial challenge in evaluating a real option.

The quantitative methods for valuing real options derived from Black-Scholes option model (1973) in financial market. 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 (1988) examined the strategic bargaining value of flexibility in a firm's negotiations with suppliers.

3. Historical Evolution of Wireless Networks

Over the past decade, wireless networks have moved 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. These latter networks provide both wireless and Internet services.

First Generation Wireless Network: The first generation (1G) wireless network was based on analog technology (IEC forum, 2003). Figure 2 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. The MSC also performs all of the network management functions, such as call handling and processing, billing and fraud detection. The MSC is interconnected with the Public Switch Telephone Network (PSTN) via trunks and a tandem switch. The main 'first generation (1G) wireless network' technology standards are *AMPS*, *TACS* and *NMT* (Dahlman et al., 1998).



Second Generation Wireless Network: The second generation (2G) wireless networks use digital transmission technology (Garg, 2001). As seen in Figure 3, the 2G network architecture has introduced new network architecture. First, the 2G system reduced the computational burden of the 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 the MSC. Second, the 2G system uses digital voice coding and digital modulation. Finally, the 2G provides dedicated voice and signaling between MSCs, and between each MSC and the PSTN.

In contrast to the 1G system which were designed primarily for voice, the 2G has been specifically designed to provide some data services. 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* (Dahlman, 1998), can be seen as straightforward upgrades of second generation networks, since in most cases, the 2G infrastructures underwent simple software/hardware developments.





Third Generation Wireless Network: Today the wireless network architecture is moving towards the third generation (*3G*) of wireless technologies, which is designed to provide voice and high-rate data service. The *3G* system can provide multi-megabit Internet access with an "always-on" feature and data rates of up to 2.048 Mbps for multimedia services. 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.

The *UMTS* was developed in 1996 with the sponsorship of the European Telecommunications Standards Institute (*ETSI*). In 1998, it was added to the International Mobile Telecommunications-2000 (*IMT*-2000) standards. It is also known as Wideband *CDMA* (*WCDMA*) because its infrastructure includes several *WCDMA* standards. *WCDMA* technology is an air interface standard in *UMTS* (Dalal, 2002). '*cdma2000*'is another wireless standard designed to support *3G* services as defined by the *ITU* and its *IMT*-2000 (Carsello, 1997). '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).

The network architecture of *UMTS* is divided into the radio access network (*RAN*) and the core network as shown in Figure 4. 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 Controller (*RNC*). The core network (focused on packet domain) includes two network nodes: the serving GPRS support node (*SGSN*) and the gateway *GPRS* support node (*GGSN*). The *SGSN* monitors user location and performs security functions and access control. The *GGSN* contains routing information for packet-switched attached users and provides inter-working with external packet-switched networks.



Figure 4: The Third Generation Wireless Network (UMTS)

4. Technology Options in Wireless Networks

Figure 5 shows the possible technology transition scenarios. A carrier can implement one of three 2G technologies: 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 today's 2G circuit-switched data connections. 2.5G offers more bandwidth than 2G but less than 3G. Wireless network operators can implement 2.5G much more cheaply 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 often considered a stepping-stone to 3G. As the wireless industry moves toward 3G technologies, the current coexistence of three major technologies will most likely evolve into two competing technologies within the 3G market: *WCDMA* and *cdma2000*.



Figure 5: Technology Options in Wireless Networks

There are several migration path scenarios from 2G to 3G for the wireless network operators, but currently the 3G world is split into two alternatives: 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*.

GSM-based Network Migration Path

Figure 6 shows the migration path scenario from *GSM* (2G) to *GPRS* (2.5G) and to *WCDMA* (3G). When *GPRS* service is provided in the *GSM* network, several 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 carriers' networks. In addition it is not possible to operate in a *GSM* mode within the same 5 MHz band. Since *UMTS* does not reuse the *GSM* base station hardware, operators must install new hardware cabinets adjacent to existing systems.



Figure 6: GSM-based Network Architecture

Table 2 briefly summarizes what components are upgraded or replaced in GSM-based networks. In case of provisioning *GPRS* service, software upgrades with little hardware replacement is needed. For *UMTS*, in contrast, most 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 for a significant investment for *3G* under the *GSM*-based network architecture.

Cotogory	GSM to G	SM/GPRS	GSM/GPRS to UMTS	
Category	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

Table 2: Upgrade/New Components in GSM-based Networks

CDMA-based Network Migration Path

Figure 7 shows the evolution path from a *cdmaOne*(2G) to a *cdma2000-3X*(3G) network architecture. 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. Because of this, the transition from *cdmaOne* to *cdma2000-1X* is relatively easy for operators and transparent for consumers. Wireless service operators can gradually migrate from '*cdmaOne*' to *cdma2000* at the *cdma2000-1X* (1.2288 Mcps) rate. As users migrate to the new standard, network operators can swap out cdma2000 1X radios and insert a *cdma2000-3X* radio to increase cell capacity. They also have the choice of using three *cdma2000-1X* radios or converting to a single *cdma2000-3X* radio. The *cdma2000* reuses the same 9.6 kbps *vocoder* from *cdmaOne*.





As seen in Table 3, 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 the introduction of new handsets. *cdma2000-1X*, which can be implemented in existing spectrum allocations, delivers approximately twice the voice capacity of *cdmaOne*, and provides average data rates of 144kbps. The *cdma2000-3X* standard is used to signify three times 1.25 MHz or approximately 3.75 MHz. The *cdma2000-3X* multi-carrier approach, or wideband *cdmaOne*, is an important part of the evolution of *IS95*-based standards. In short, *cdma2000-3X* with data rates of up to 2Mbps offers greater capacity than *cdma2000-1X*.

Catagory	cdmaOne to	cdma2000 1x	Cdma2000 1x to cdma200 3x	
Category	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

Table 3: Upgrade/New Components in CDMA-based Networks

5. The Model: Assessing Technology Migration Options

In this section, we develop a model to assess strategic options in the migration to the 3G wireless network architecture from 2G. Using real option theories, this study attempts to calculate the transition value when moving from generation-to-generation (inter-generational transition) and within the same generations (intra-generational transition).

Let the value of technology investment in the revolutionary technology (i.e. *CDMA*based) compared with the evolutionary (i.e. *GSM*-based) be '*H*'. Also let *P* and *B* be the net 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'). Assuming that the level of investment for improving network performance is directly related to their revenues, the key issue in the choice of strategic options is how to quantify a trade-off between the level of performance improvement 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.

We treat the choice between the two scenarios as a comparison between two wireless network 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 $(W_{REV}) = v_P P$ (i.e. *CDMA*-based architecture)
- Evolutionary portfolio $(W_{EVO}) = v_B B$ (i.e. *GSM*-based architecture)

where v_P and v_B are amounts invested in each scenario.

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

$$v_H H + W_{EVO} = W_H + W_{EVOt} = W_{REV}$$

Using the derivative, it can be described as:

$$v_H dH(P, B) = v_P dP - v_B dB$$

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

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

One way to interpret EQ.(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 $W_H = W_{REV} - W_{EVO}$ as the value of the premium that should be paid to accomplish higher network performance, under the assumption of risk neutrality. H(P,B) quantifies 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.

Now let's consider the time horizon τ to deal with a continuous option, like Europeantype 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:

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

$$\beta = \frac{1}{H} \left\{ \frac{\partial H}{\partial t} + \mu B \frac{\partial H}{\partial B} + \alpha P \frac{\partial H}{\partial P} + \frac{1}{2} \left\{ \delta^2 B^2 \frac{\partial^2 H}{\partial B^2} + 2\rho \sigma \partial B P \frac{\partial^2 H}{\partial B \partial P} + \sigma^2 P^2 \frac{\partial^2 H}{\partial P^2} \right\} \right\}$$
(3a)
$$\gamma = \frac{\sigma P}{H} \frac{\partial H}{\partial P}$$
(3b)
$$\eta = \frac{\delta B}{H} \frac{\partial H}{\partial B}$$
(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):

$$\frac{dP}{P} = \alpha \, dt + \sigma \, dz \quad (4a)$$
$$\frac{dB}{B} = \mu \, dt + \delta \, dq \quad (4b)$$

The fact that high QoS technology has less variability here could mean that: $0 < \delta < \sigma$. To allow the possibility of correlations between the stochasticities of B(t) and P(t), we assume that: $\langle dz.dq \rangle = \rho dt$, where $-1 \le \rho \le 1$. Equation (2) corresponds in fact to three equations. The coefficients of dt, dq and dz must separately satisfy the equation. Using Equation (4a), (4b), (3), and (2) yields the three equations:

$$\frac{W_{Bt}}{W_{H}} = \frac{(\beta - \alpha)}{(\alpha - \mu)} = \frac{(\gamma - \sigma)}{\sigma} = -\frac{\eta}{\delta}$$
(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 $x = \frac{B}{P}$):

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

Another key observation stems from Equation (5) combined with Equation (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 with Equation

(3a), leads to:

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

This equation is a differential equation for the derivative $H(B, P, \tau)$. Using $x = \frac{B}{P}$ and Equation (7) and (8) become:

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

 $V^2 = \sigma^2 - 2\rho\sigma\delta + \delta^2$ 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 τ . By definition of

T, $dT = -V^2(t)dt$, and Equation (10) can be written:

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

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

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

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

If one defines: $y = \log(x)$, $\frac{dx}{x} = d\zeta$ becomes: $dy = -\frac{dT}{2} + d\zeta$ The backward Kolmogorov

equation for y is³:

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

If f(y) = h(y, T = 0), the solution of Equation (11) is⁴:

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

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

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

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

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

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

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

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

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

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

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

With:

$$d_{1}(x,T) = \frac{1}{\sqrt{2T}} \left[Log(x) + \frac{T}{2} \right]$$
(15a)
$$d_{2}(x,T) = \frac{1}{\sqrt{2T}} \left[Log(x) - \frac{T}{2} \right]$$
(15b)
$$\Phi(d) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{d} e^{-\eta^{2}} d\eta$$
(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 $_{H(B,P,T)=Ph(x,T)}$, 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):

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

In Equation (16), $T = (\sigma^2 - 2\rho\sigma\delta + \delta^2)\tau$ is the cumulative uncertainty over the time horizon " τ ". When $\sigma \gg \delta$, $T \approx \sigma^2 \tau$. When the variability is zero, Equation (16) becomes: H(B, P, 0) = Max[0, P - B]. 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 higher QoS technology, is exactly equal to H(B, P, T), the investor is in a "risk neutral" situation.

6. Research Design and Implementation

Figure 8 illustrates the overall design of this study to determine the best technology transition path. Two types of technology migration paths are identified: (1) *Inter-Generational Technology Migration Path* and (2) *Intra-Generational Technology Migration Path*. First, *Inter-Generational Technology Migration Path* 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 Path*, 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.



Scenarios and Assumptions

The scenarios demonstrate the possible transitions of wireless technology and how they might change the value of networks. These scenarios are based on assumptions that had to be made about the future. That the future follows these suggestions is extremely unlikely, but still the scenarios may provide a firm's manager with some new views and foster the own creativity in thinking about the influence of new technology.

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

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

Based on these assumptions, the following alternative technology migration paths are developed based on the technology options diagram in Section 2.

- 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

Data Collection

Since one of the implicit aims of this study is to understand how the real options approach can be used as a model for technology choice, we simplify matters where possible. For example, taking into account all the problems of reaching relevant data on technological development, we assume that the only available data are on current market shares of competing technologies in generation. We hope to use more refined and enriched data in future research.

Figure 9 plots the number of subscribers in each wireless technology from 1992 to 2004 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 9: Wireless Market Size

Based on the number of subscribers in generation (Figure 9), Figure 10 shows market shares for the various technologies in the US wireless industry. 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 10: Market Share of Wireless Technologies

7. The Results

Before we get into specific scenario results, it is worth making a note on interpreting the graphs in the subsequent sections. They are based on market share data, which represent actual consumer behavior and are thus backward looking, rather than on expected market share, which are forward looking. Thus these graphs do not have strong predictive power, but, in line with the objectives of the paper, are intended to illustrate how real options can be applied.

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

The first scenario is to move from Analog to *TDMA* network architecture in the US. Figure 11 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. Analog technology in the US has been popular for a long time, partly because it served as the basic technology in an environment with incompatible 2G standards. 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 11: The Value Curve of Technology Transition (Analog to TDMA)

Figure 12 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 IG to 2G is desirable starting in 2001 or later.



Figure 12: The Value Curve of Technology Transition (Analog to GSM)

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 13). *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 13: The Value Curve of Technology Transition (Analog to CDMA)

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

The next scenario (Figure 14) 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 14: The Value Curve of Technology Transition (*TDMA* to *GSM*)

Another 2G scenario (Figure 15) 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 15: The Value Curve of Technology Transition (TDMA to CDMA)

Figure 16 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 16: The Value Curve of Technology Transition (GSM to CDMA)

Transition Towards 3G

Figure 17 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 17: The Value Curve of Technology Transition (GSM-WCDMA)

The next scenario (Figure 18) displays the value curve when moving from *CDMA* to *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 18: The Value Curve of Technology Transition (CDMA-cdma2000)



8. Concluding Remarks

8.1 Summary

In this paper, we investigated the historical evolution of wireless technologies from the first generation (1G) to the second generation (2G) and the third generation (3G) wireless network technologies. Based on the real options approach (ROA), we also developed a model to assess the transition (replacement) from old technology (premium value) to new technology (option value). Finally, we assessed the migration options of wireless network technologies in the US using our technology transition assessment model as a case study.

The results of all technology transition scenarios in the US wireless industry are summarized in Figure 198.

- First, moving from analog to any 2*G* 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.
- Second, 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. Note that this changes when market data from the world is used instead of just US data.
- Third, 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 19: Technology Migration Path Diagram

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.

8.2 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 paper.

First, the US market with a suite of different technologies in use offers an interesting laboratory to test the real options approach as a strategic decision tool. Based on this preliminary practice of our real options model, we would like to develop a theory for a firm's behavior analysis to solve strategic issues in the company level: for example, why do not all of the firms in wireless network industry to migrate or upgrade for the *3G* services at the same time? Or why did some companies choose *WCDMA* instead of *cdma2000* (i.e. AT&T wireless and Cingular), or else?

Second, 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.

Third, the other future research to come from this study 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.

Finally, we hope that this study will take the form of helping wireless network service providers for a strategic decision to upgrade or migrate for the next generation network technologies and architectures, by resolving the ambiguity of the nature of network evolution. Finally, since still the areas of the next generation wireless network technologies and architectures remains in its debating stages of development with no substantial implementation results, there is much work to do. With the further research, the scope of study can be developed.

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