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Real Options: Strategic Technology Migration Options in Wireless Industry

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ABSTRACT

The major US wireless operators already have announced their plans for evolution of their networks, but some uncertainties remain, such as emergence of new technologies (WiMAX and WLAN) and consolidation among operators (AT&T Mobile and Sprint Nextel). The paper proposes a real option based model for technology decisions and applies it to the US wireless industry as a case study. We also discuss what decisions are made, what the outcomes are, and how the options model is validated. The preliminary results show that the evolution of wireless network technologies between generations (*inter-generations migration scenario*) is desirable (a positive net option value), but not desirable (a negative net option value) within generations (*intra-generation migration scenario*).

Keywords

Real Options, Technology Migration, Wireless Networks, 3G

INTRODUCTION

In the late 1990s, AT&T Wireless and Cingular Wireless each faced a critical decision. The TDMA technology that they chose earlier that decade was approaching obsolescence; the data communications features that were beginning to be demanded by the marketplace had not been developed for this technology platform, nor would they be by equipment manufacturers. Thus, to remain competitive in the marketplace, these mobile service providers had to switch to a CDMA or GSM-based platform. This transition meant replacing all of their base station and switching hardware as well as customer handsets in an orderly fashion. Although both carriers ultimately chose GSM (and ultimately merged to become today's AT&T Mobile), the decision process has received little attention in the literature despite the enormous business and financial risks involved. This paper uses this decision, using the information available at the time, to propose the real options based model for technology decisions.

By early 2007, the US wireless market (CTIA, 2006; FCC, 2006) was dominated by AT&T Mobility, Verizon Wireless and Sprint Nextel, together accounting for more than 70% market share. T-Mobile, Alltel and US Cellular make up the next tier, accounting for about 20%. In 3G networks, Verizon Wireless and Sprint Nextel provided cdma2000 technology, while AT&T Mobility and T-Mobile offered WCDMA technology. Recently, Sprint Nextel began deploying a WiMAX network, preparing for the next round of competition, in 4G technologies (Polivka, 2007).

As seen in Figure 1, the current US wireless market simply can be broken down into two dimensions; three types of customer groups and three types of network operator 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 (Actually 1G service was stopped after 2004 in the US), and 3) Third group is customers who move from their current *2G* services. In the network operator groups, 1) Firm A-type group is the existing hybrid service providers offering *1G* and *2G* technologies, like Verizon and 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. 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, the issues are; 1) how to assess the value of technology migration as a basis of technology migration strategy? 2) what is a firm's migration strategy for 3G including what technology, when, and how to migrate ?

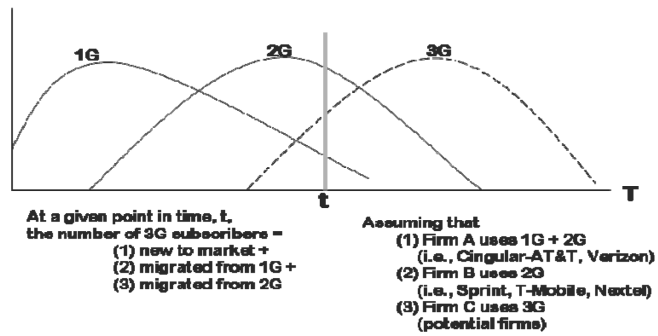

Figure 1. Market Structure and Operator Groups

The goal of this study is to develop a theoretical framework using the real options approach (ROA) for wireless operators to support their strategic decisions when considering technology choices as they move to the next generation networks. Our study does not give an absolute value for the choice of technology, but provide some inferences by attempting to quantify the value of technology migration strategy as a basic element of strategic decision-making. As a result, this study intends to raise core issues concerning the transition towards *3G*.

The real options approach RROA) has been applied to several industries, such as oil (Paddock *et al.*, 1988), mining (Kemma, 1993), pharmaceutical (Micalizzi, 1999), airline industry (Stonier, 1999), and electricity (Deng et al., 2001). Recently, along with the wide acceptance of real options, many academics and practitioners are actively working to apply real options in the information and communications technology (ICT) sector (Clemons, 1991; Kumar, 2002; Benaroch, 2002; Alleman & Rapport, 2006) have recognized the importance of utilizing the theory of real options to justify the option-like characteristics of ICT investments. Although the theory of real options provides a theoretically rigorous framework to analyze the optimal exercise of options, people have expressed a number of concerns related to the efficacy of applying option pricing theory to ICT sector. The focus of this paper is on the applications of real options methodology to the ICT sector, especially wireless industry. We hope this will give the reader a good foundation to begin understanding and appreciating the significance of this approach.

THEORETICAL FRAMEWORK

Real Options: A Brief Overview

The options paradigm in investment decision-making began from Black-Scholes(1973)' option theory, which offered some valuation tools under the underlying sources of uncertainty with continuous time, assuming 'Brownian motions (random walk)'. Brennan & Schwartz (1985) and McDonald & Siegel (1986) were the first to actually employ options thinking in the valuation of real assets (i.e., projects), which has become known as 'real options'. After following them, Dixit & Pindyck (1995) and Trigeorgis (1996) deal with the issue of the timing of investment when there is competition in the product market. After that, real options have been popular in several industries, such as oil (Paddock, 1988; Pickles & Smith, 1993), mining (Brennan & Schwartz, 1985), pharmaceutical research (Micalizzi, 1999), information technology (IT) (Benaroch & Kauffman, 2000; Kim & Sanders, 2002), and other investment activities (Deng et al., 2001; Cheng et al., 2005).

Real options are simply defined as *the right, but not the obligation* to take some actions in the future (Dixit & Pindyck, 1995). That is, real options involve discretionary decisions or rights without any obligation to acquire or exchange an asset for a specified alternative price (Amram & Kulatilaka, 1998). 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 fundamental importance of *Real Options* has been recognized in academia (Pindyck, 1989; Dixit & Pindyck, 1995; Trigeorgis, 1996; Amram & Kulatilaka, 1998; Benaroch & Kauffman, 2000; Kim & Sanders, 2002) as a strategic tool to manage uncertainty. Real option is a tool to assess potential opportunities and uncertainty as a positive value, through managerial flexibility. Managerial flexibility is a set of real options, for example, the options to defer, abandon, contract, or expand investment, or switch investment to an alternative (Trigeorgis, 1993). It is often not explicitly taken into account when comparing a project's tangible costs and benefits by the traditional, discounted cash flow approach (e.g., NPV and IRR).

The ROA may be a useful tool for a firm's technology management because firms are often faced with higher degrees of uncertainty when making strategic investment decisions.

NPV calculates the difference between the present value of cash inflows from the investment and the present value of cash outflows initially invested. If the NPV of a project results in a positive amount, the project should be undertaken. However, if NPV is negative, the project should be rejected because net cash flows will also be negative. The NPV method explicitly assumes that the project will meet the expected cash flow without any intervention by management during the process. Rather, all the uncertainty can be handled by a single risk-adjusted discount rate. That is, there is no dynamics in a project. It is static; never or now. However, the ROA has distinctive ability to capture managers' flexibility in adapting their future actions, such as waiting, staging, changing, abandoning, switching, and growing (Trigeorgis, 1996) in response to evolving markets or technological conditions. Further, it provides that uncertainty can create value by expanding a positive side (profit) and limiting a negative side (loss) by management's flexibility. This is appealing to the firms under high uncertain technology environment as a strategic technology management tool.

Technology Assessment Options Model

Definitions and Assumptions

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.

Technology Transition Option 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 $(W_{REV}) = \nu_P P$ (i.e. *CDMA*-based architecture)
- Evolutionary portfolio $(W_{EVO}) = \nu_B B$ (i.e. *GSM*-based architecture)

  where ν_P and ν_B are amounts invested in each scenario.

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

$$\nu_H H + W_{EVO} = W_H + W_{EVOt} = W_{REV}$$

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:

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

P: the present value of revolutionary technology (CDMA)
B: the present value of evolutionary technology (GSM)
W_{REV}: the weighted present value of revolutionary technology (CDMA)
W_{EVO}: the weighted present value of evolutionary technology (GSM)
H(P,B): the option value of technology migration

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.

After some manipulation (See Appendix 1), we derived 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 EQ. 14:

$$H(B,P,T) = B\cdot\Phi\left(d_1\left(\frac{B}{P},T\right)\right) - P\cdot\Phi\left(d_2\left(\frac{B}{P},T\right)\right) \quad (2)$$

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

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

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

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

Since our real option model can assess the transition value from old technology to new technology, we attempt to test the value of technology transition, from generation to generation (inter-generation transition), and within the same generations (intra-generation transition). For example, the parameters for our model consist of ***H*** (option value), ***B*** (the value new technology), ***P*** (the value of old technology) and ***T*** (accumulated uncertainty). Market shares in wireless market are used as the value of ***B*** and ***P*** because we consider that the value of technology is proportional to market power (i.e. market share). Modern, complex technologies often display increasing returns to adoption [67] in that the more it is adopted, the more experience is gained with it and the more it is improved (which is directly connected to the value of technology).

Decision Criteria Rule

As seen in equation (3), the value of the option (H) should offset the premium (P-B) at least. The premium is an opportunity cost to give up some benefits from the existing technology.

$$H(B,P,T) \geq P - B \Leftrightarrow \frac{H(B,P,T)}{B} \geq \frac{P}{B} - 1 \quad (3)$$

SIMULATION AND THE RESULTS

Research Design

Figure 2 illustrates the research design of this study. 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.

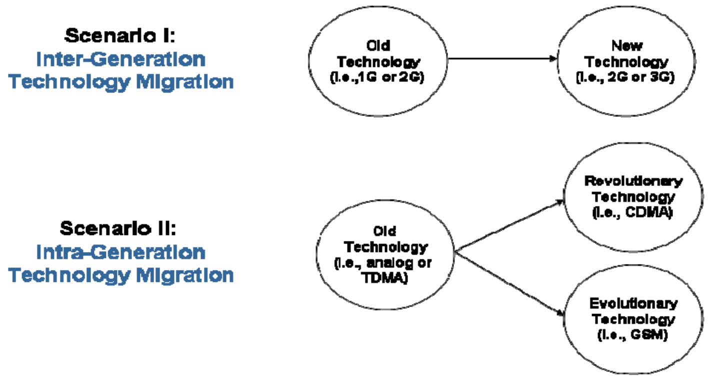

Figure 2. Research Design

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.

- Inter-Generational Migration
  Analog => TDMA, Analog =>GSM, Analog => CDMA
  TDMA => cdma2000, TDMA => WCDMA
  GSM => cdma2000, GSM => WCDMA
  CDMA => cdma2000, CDMA => WCDMA
- Intra-Generational Migration
  TDMA => GSM
  TDMA => CDMA
  GSM => CDMA

Data Collection

Figure 3 plots the number of subscribers in each wireless technology from 1990 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 was completely phased out after 2004 in the US wireless market.

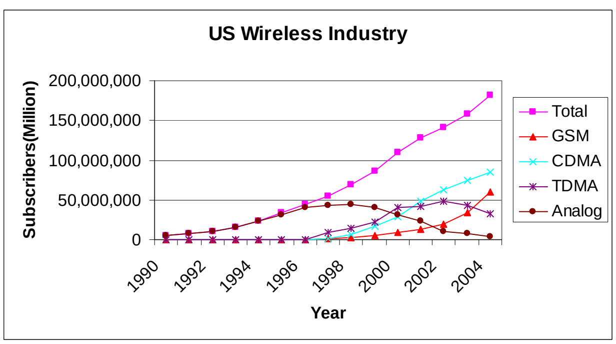

Figure 3. US Wireless Market Size

Based on the number of subscribers in generation (Figure 3), Figure 4 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.

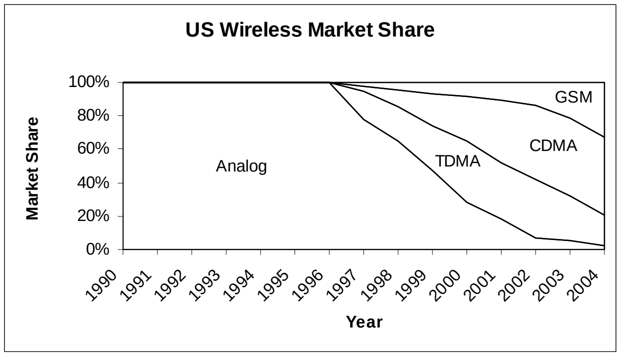

Figure 4. US Wireless Market Share

Simulation Results

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

The first scenario is to move from Analog to *TDMA* network architecture in the US. Figure 5 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.

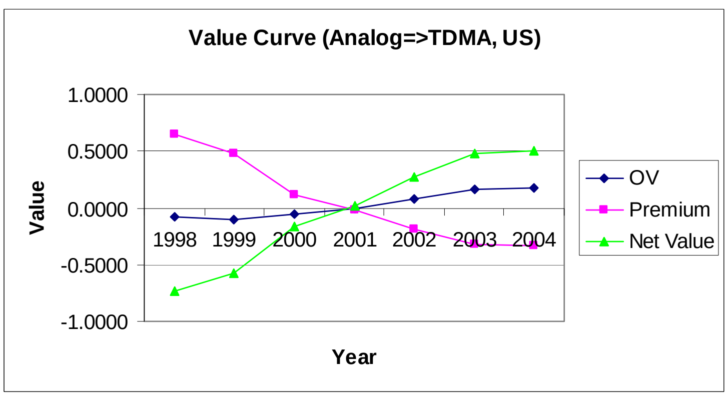

Figure 5. The Value Curve of Technology Transition (Analog to *TDMA*)

Figure 6 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.

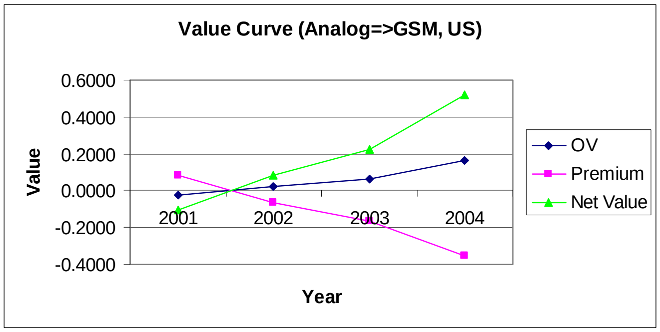

Figure 6. The Value Curve of Technology Transition (Analog to *GSM*)

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 7). *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.

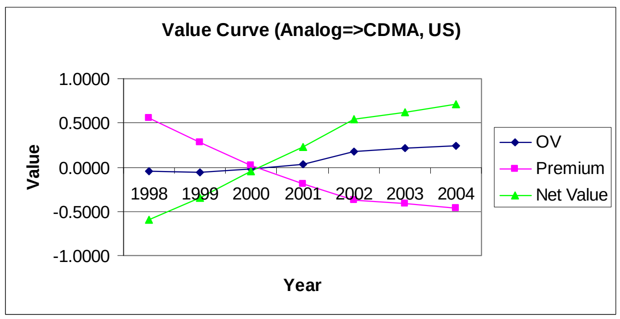

Figure 7. The Value Curve of Technology Transition (Analog to *CDMA*)

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

The next scenario (Figure 8) 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.

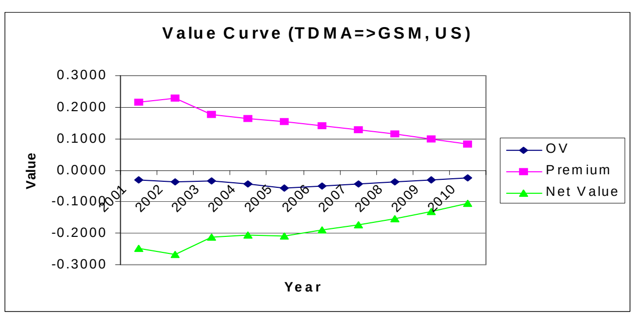

Figure 8. The Value Curve of Technology Transition (*TDMA* to *GSM*)

Another *2G* scenario (Figure 9) 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.

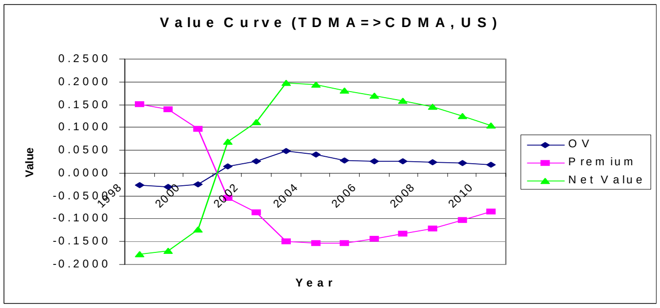

Figure 9. The Value Curve of Technology Transition (*TDMA* to *CDMA*)

Figure 10 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.

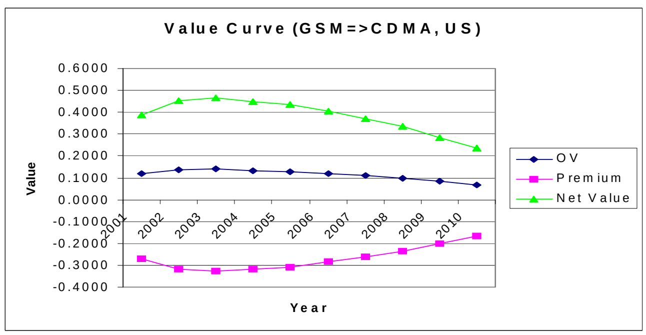

Figure 10. The Value Curve of Technology Transition (*GSM* to *CDMA*)

Transition to 3G

Figure 11 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.

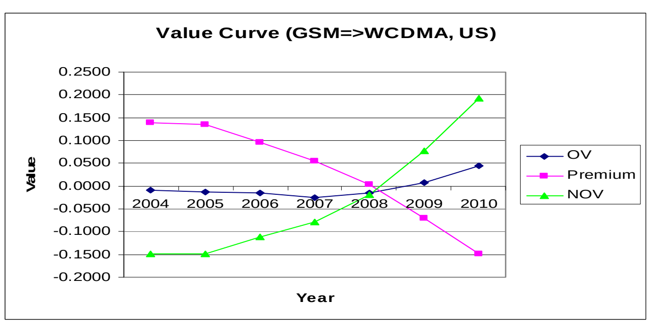

Figure 11. The Value Curve of Technology Transition (*GSM* to *WCDMA*)

The next scenario (Figure 12) 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.

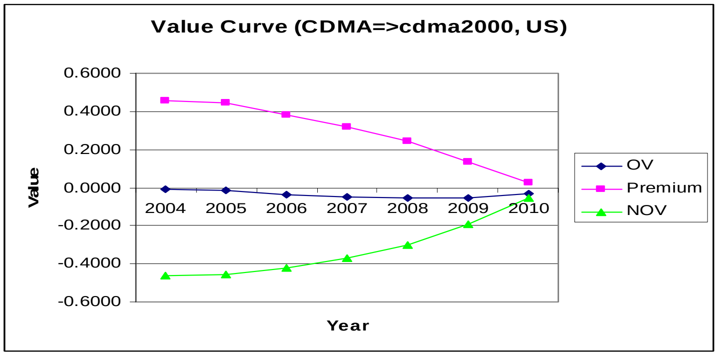

Figure 12. The Value Curve of Technology Transition (*CDMA* to *CDMA2000*)

STRATEGIC DECISIONS FOR TECHNOLOGY EVOLUTION

The major US wireless operators already have announced their plans for evolution of their networks, but some uncertainties remain, such as emergence of new technologies (WiMAX and WLAN) and consolidation among operators (AT&T Mobile and Sprint Nextel). In addition, TDMA-based operators are not yet clear which technology path is taken.

Now, we discuss what decisions were made, what the outcomes were, and how the options model was validated. Figure 16 summarized the assessment results of all technology transition scenarios in the US wireless industry.

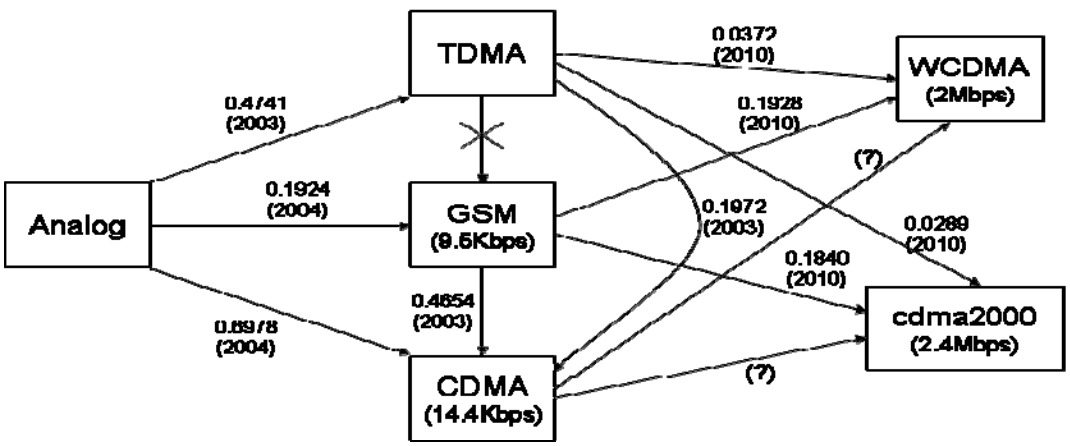

Figure 13: Summary of Technology Evolution Assessment

Stage I: Analog to 2G(Inter-Generation Migration)

Moving from analog to any *2G* technology is desirable (all positive); however, the best choice for analog carriers is to move to *CDMA* in 2004 because it showed the highest option value (0.6978) of the three possibilities (*TDMA*, *GSM*, and *CDMA*). From 2000 to 2004, *TDMA* was a leader in market, but *CDMA* was rapidly growing market share with high capacity and call quality, although it was not matured technology (high uncertainty). As a result, the US wireless market was dominated by *CDMA*-based operators (i.e., Verizon Wireless and Sprint, together accounting for more than 50% in the US wireless market) in 2004. So, our result using the model was shown right direction in technology evolution path.

Stage II: 2G to 2G (Intra-Generation Migration)

Until now, three popular 2G technologies (i.e., *TDMA*, *GSM*, and *CDMA*) have competed in the US wireless market.

First, let's look at a scenario moving *TDMA* to *GSM*. The result shows that it is not desirable because all transition values during experimental periods (from 2001 to 2010) are negative. This result conflicts with the current US wireless industry. Many *TDMA*-based operators including AT&T Mobile changed into GSM network. Next, moving from *TDMA* to *CDMA* is desirable in our model because of the positive net option value of 0.1972 in 2003. However, there was no company to transit from *TDMA* into *CDMA* in the US wireless market. The last scenario is to move from *GSM* to *CDMA*. In the case of *GSM*-based operators, moving to *2G CDMA* is recommended because of the positive transition option value (0.4654) in 2003.

Then, why are the results by option model and the operators' decisions not consistent in intra-generation scenarios? Does it fail to validate our option model? If not, how can we explain this gap? At this point, although our model could not explain it, intuitively the transition costs between incompatible technologies (i.e., *TDMA* and *CDMA*, *GSM* and *CDMA*) may exceed potential revenues (i.e., option value). And another reason is that only market (macro) data is available for technology assessment in our study. If we use data of an individual firm, we may draw more meaningful results.

Stage III: 2G to 3G (Inter-Generation Migration)

The transition from *GSM* to *3G* has a similar positive option value for *WCDMA* (0.1928) and *cdma2000* (0.1840) in 2010. In reality, *WCDMA* deployment is already de facto evolution. Many *GSM*-based mobile operators are considered *WCDMA* as the preferred evolution path because many *GSM-based* operators are from Europe and only considers *WCDMA* migration for technical and political reasons. Since new radio access network (UTRAN) needs to be deployed, *WCDMA* evolution requires substantial new investment for *GSM*-based operators. So, *GSM*-based operator may consider step-by-step evolution (i.e., *GSM-GPRS*) towards 3G, by minimizing initial infrastructure investment.

If *GSM*-based operators choose c*dma2000* (even unlikely), there are two possible strategies; one is to maintain a parallel *cdma2000* network and the other is the integration of *cdma2000* network within the *GSM* network. The former is more costly with running double networks, but supports more favorable market requirement. The latter is less costly with a single overlaid network, but higher coverage (i.e., lower population density areas).

CDMA operators 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. The evolution path from *2G CDMA* (*cdmaOne*) to *cdma2000* appears technically and economically straightforward, by minimizing initial infrastructure investment. The evolution of *CDMA*-based (i.e., cdmaOne) network to cdma2000 is already taking place on significant scale. For *CDMA*-based operators, *cdma2000* evolution would require minimum investment and smooth transition without any technical difficulty. *cdma2000* evolution refers to the subsequent evolution steps for current *cdmaOne* operators; from *DO* (data only) to *DV* (data and video). Sprint PCS moved directly from *cdma 1X* to *DV*.

The *WCDMA* evolution of *CDMA*-based operators would be a completely new network being overlaid on the existing *CDMA* installed base, so it seems unlikely. However, it may happen by regulatory or political factors. For example, partly owned (40%) by the Vodafone Group in UK, Verizon wireless has been started pressure to integrate Verizon's network (*CDMA*-based network) into Vodafone's network (GSM-based network), with centralized service development and common technology platforms. This suggests that Vodafone may aim to eventually force Verizon onto *WCDMA* evolution.

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. However, the *TDMA* evolution is controversial. Actually *TDMA*-based operators cannot evolve directly to 3G, but must choose between a *CDMA*-based path and a *GSM*-based path.

CONCLUDING REMARKS

The paper overviewed wireless technologies from *1G* to *2G* and *3G*, and investigated its technology options with two technology migration paths. We proposed a real option based model for technology decisions and applied it to the US wireless industry as a case study. We also discussed what decisions were made, what the outcomes were, and how the options model was validated. The preliminary results show that the evolution of wireless network technologies between generations (*inter-generations migration scenario*) is desirable (a positive net option value), but not desirable (a negative net option value) within generations (*intra-generation migration scenario*).

Managerial Implications

The main theme of this paper, '*The Application of Real Options to Technology Management*', introduces a new perspective on the technology management field, such as options thinking in technology choice. This study attempts to simplify the theory and show how to use real options from choosing theory, analyzing problems, and to developing a simple model. One of the most popular criticisms of real options is that it is too descriptive and difficult to apply on real world, although it is recognized as an excellent theory. Another objection is that the approach is buried too deeply in mathematics and it is difficult to extract the meaning of the results. This paper will contribute to make real options easier to use.

The findings of our 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.

In a practice, this study intends to raise core issues concerning the transition to *3G*. Consequently, this study will help wireless operators 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. That is, wireless operators may find it worthwhile to evaluate new technologies using the ROA as strategic technology options. 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.

Limitation and Future Research

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 (i.e., macro data) of competing technologies in generation. We hope to use more refined and enriched data in 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*, 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, this study will take the form of helping wireless network service operators for a strategic decision to migrate their existing networks toward the next generation networks, by resolving the ambiguity of the nature of network evolution. Since still the areas of the next generation wireless network technologies and architectures remain in the debating stages with no substantial implementation results, the scope of study can be expanded with the further research in the future.

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