ABSTRACT

The wireless industry is challenged by the rapid development of wireless network architecture and technologies due to the increasing demand for high-quality multimedia services. This demand has led wireless service providers to struggle with a network migration problem, i.e., how to best deliver high-quality multimedia services. 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 currently in the process of modifying their networks to offer subscribers 3G services.

This study assesses the wireless technology migration path options towards the third generation (3G) wireless data service network architecture design. Based on the real options theory, we develop a theory to support the decisions of wireless network service providers: to migrate or not, if so, which network migration path to take and what to do once they get there.

1. Introduction

With the rapid development of wireless network technologies and architectures and the increasing demands of multimedia services, wireless service providers worked to migrate their networks to be capable of delivering high speed packet switched data services. These data services are the underpinning of multimedia and interactive information systems that service providers expect to be a cornerstone of future profits. To that end, equipment providers have been developing a series of technologies, referred to as the Third Generation mobile or 3G, to support these services. Since the complete replacement of the existing wireless network architecture is not practical and 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 get there, to uphold competitive advantages under a severe competition.

At present, the evolutionary paths to 3G from the principal 2G technologies, GSM and CDMA are quite distinct. One calls for substantial infrastructure replacement while the other calls for upgrades to existing equipment. There are many alternative wireless network technologies, such as TDMA, GSM, GPRS, EDGE, WCDMA, cdma2000, etc. These abundant choices of wireless technologies require service providers to examine the options for their network evolution as a strategic decision.

This study introduces the real options approach to assess the migration path options towards the third generation (3G) wireless data service network architecture design. Based on the real options theory, we develop a theory to support the decisions of wireless network service providers: to migrate or not, if so, which network migration path to take and what to do once they get there. We explore two typical network architecture-based migration alternatives: the ‘Global Systems for Mobile Communications (GSM)-based’ network scenario and the ‘Code Division Multiple Access (CDMA)-based’ network scenario, as strategic options for facilitating to migrate into the next generation network architecture. One calls for substantial infrastructure replacement (architectural innovation), while the other
calls for upgrades to existing equipment towards 3G (*modular innovation*). In this study we blend a comparative study and a ‘what if’ study (or contingency study) by examining two wireless network migration scenarios.

### 2. Theory Development

#### 2.1 Real Options Theory

Options 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 (1973) 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 (1985) 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 (1995) 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 (Dixit and Pindyck, 1994).

Flexibility is at the core of real option theory, especially management’s flexibility. The value of management’s flexibility is often not explicitly taken into account by the traditional approaches, such as discounted cash flow approaches (e.g., NPV and IRR). The ultimate in flexibility is achieved if investments are fully and costlessly reversible. For example, firms can reverse all investments that are not optimal for current economic conditions and invest in the capital market that is instantaneously optimal. The value of management’s flexibility is basically a collection of real options, which can be priced with the techniques used in financial options.

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 the right but not the 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 a lot from its value to another firm. This creates a substantial challenge in evaluating a real option.

The traditional financial option pricing models, such as the Black-Scholes model (1973) or the Cox/Ross/Rubinstein binomial model (1979), can be applied to real options. However, since these methodologies basically require the existence of a market priced asset, it is difficult to apply them directly into real options. In reality, many cases in system design cannot be tracked to its market price because it (incomplete or testing system) is not traded in the market. Baldwin & Clark (2000) develop a new real options model without assuming the market value of asset. Their theory is based on the idea that modularity adds value in the form of real options. They argue that a module creates an option to invest in a search for a superior replacement and to replace the currently selected module with the best alternative discovered,
or to keep the current one if it is still the best choice. Intuitively, the value of such an option is the value that would be realized by the optimal experiment-and-replace policy. They do not assume that tracking assets exist. Rather, their option valuation formula is statistical, which assumes that the added values of independently developed alternatives to existing modules are normally distributed.

2.2. Theory and Model

In this section, we develop a theory to assess strategic options towards the 3G from 2G mobile communication system architecture.

In our study, real options can be defined simply as opportunities to respond to changing circumstances of a project (or a strategy) by management. For example, in the case of 3G, wireless carriers have a strategic choice for migrating their networks, ‘CDMA-based’ or ‘GSM-based’, according to their situation.

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:

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

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:

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

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. $H(P, B)$ quantify 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 (Kim 2004), we write 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:

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

(2)

With:

\[
d_1(x,T) = \frac{1}{\sqrt{2\pi}} \int \left[ \log(x) + \frac{T}{2} \right] \, dx
\]

\[
d_2(x,T) = \frac{1}{\sqrt{2\pi}} \int \left[ \log(x) - \frac{T}{2} \right] \, dx
\]

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

In equation 2, \( T = \left( \sigma^2 - 2\rho\sigma\delta + \delta^2 \right) \) is the cumulative uncertainty over the time horizon “t”. When \( \sigma >> \delta \), \( T \approx \sigma^2 t \). 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. If the premium associated with evolutionary technology, is exactly equal to \( H(B, P, T) \), the investor is in a “risk neutral” situation.

3. Historical Evolution of Wireless Networks

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.

3.1 First Generation Wireless Network

The first generation (1G) wireless network was based on the analog technology which was 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 forum, 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 1 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). In the USA, Advanced Mobile Phone System (AMPS) (Rappaport, 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) (Rappaport, 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. It is the common Nordic standard for analog mobile telephony as established by the telecommunications administrations in Sweden, Norway, Finland and Denmark in the early 1980s.

3.2 Second Generation Wireless Network

The second generation (2G) wireless networks emerged with the advent of digital transmission technology. As seen in Figure 2, the 2G network architecture introduced a new network architectures. 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 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.

Time division multiple access (TDMA) (Garg, 2001) 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. 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.

Global system for mobile communication (GSM) (Rappaport, 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. 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 (Gargo, 2001). The GSM is used in the 900 and 1800 MHz bands all over the world except for North America (1900MHz band).

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

High Speed Circuit Switched Data (HSCSD) (Garg, 2001) 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 (Rappaport, 1996).

The CDMA technology (Gargo, 2001) 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. The CDMA have claimed bandwidth efficiency of up to 13 times that of TDMA and between 20 to 40 times that of analog transmission.

3.3 Third Generation Wireless Network

Nowadays the wireless networks are moving to third generation (3G) technologies, which provide the high-rate voice and data service. 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. 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 it's infrastructure includes several WCDMA standards. WCDMA technology is an air interface standard in UMTS (Dalal, 2002). The WCDMA technology uses direct spread spectrum 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. As a 3G standard, it offers a packet-based wireless service with rates up to 2.048 Mbps and the anticipation to reach the 8 Mbps platform in the years to come. A 5 MHz, UMTS channel can support 100 to 350 voice calls at once using a much more efficient modulation technique than GSM. It is important to note that the 5 MHz frequency band was not chosen randomly.

The network architecture of UMTS is divided into the radio access network (RAN) and the core network as shown in Figure 3. 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 (PS) attached users and provides interworking with external PS networks such as the packet data network (PDN).

Figure 3: 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’ 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). 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. 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). Within this standard, mobile users seize a 1.25 MHz FDD or TDD channel. The cdma2000-1xEV is a High Data Rate (HDR) packet standard originally developed by Qualcomm, Inc. The cdma2000 1xEV-DO is obtainable to suit demanding
applications such as video streaming and large file downloads. Finally, the cdma2000-3xRTT is a future standard that will use 3, 1.25 MHz radio channels simultaneously to create a "super channel" and provide outstanding data rates (3.09 Mbps) for every user.

4. Technology Options in Wireless Network

Figure 4 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 today’s 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.

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. 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 4: Technology Options in Wireless Networks](image)

There are several migration 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.

4.1 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 \textit{GSM} mode and a \textit{UTRA} mode within the same 5 MHz band.

As shown in Figure 5, when \textit{GPRS} service is provided in the \textit{GSM} network, several components are added, like \textit{SGSN} and \textit{GGSN} (yellow shaded boxes). Further, a transition from \textit{GSM/GPRS} to \textit{UMTS} (3G), access network section (blue shaded boxes) is totally changed or added in the networks.

Table 1 briefly summarizes what components are upgraded or replaced in the networks. In case of provisioning \textit{GPRS} service, it needs simply the upgrades of software nearly without replacement of hardware. While, in case of provisioning \textit{UMTS}, most of access network facilities are changed because the technology in \textit{GSM/GPRS} (TDMA-based) is totally different from \textit{UMTS}'s technology (CDMA-based). This means that a significant investment is required for 3G under the \textit{GSM}-based network architecture.

![Figure 5: GSM-based Network Architecture](image)

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

\textbf{Table 1: Upgrade/New Components in GSM-based Networks}
4.2 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 smaller capital investments. Because of this, the transition from cdmaOne to cdma2000-1X is relatively easy for operators and transparent for consumers. A service provider 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. Figure 6 shows the cdma2000-3X network architecture.

![CDMA-based Network Architecture](image)

As seen in Table 2, 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 for users who wish to take advantage of the capabilities of the upgraded system. The cdma2000-1X, which is 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 multicarrier 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.

So, unlike a case of UMTS, cdma2000 does not require as much investment to enable 3G services.
<table>
<thead>
<tr>
<th>Category</th>
<th>cdmaOne to cdma2000 1x</th>
<th>Cdma2000 1x to cdma2000 3x</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HW</td>
<td>SW</td>
</tr>
<tr>
<td>Mobile Station (MS)</td>
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</tr>
<tr>
<td>Base Transceiver Station (BTS)</td>
<td>No Change</td>
<td>Upgrade</td>
</tr>
<tr>
<td>Base Station Controller (BSC)</td>
<td>No Change</td>
<td>Upgrade</td>
</tr>
<tr>
<td>Mobile Switching Center (MSC)/</td>
<td>No Change</td>
<td>Upgrade</td>
</tr>
<tr>
<td>Visitor Location Register (VLR)</td>
<td>No Change</td>
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<tr>
<td>Home Location Register</td>
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<td>Home Agent (HA)/FA</td>
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<td>New</td>
</tr>
<tr>
<td>AAA Server</td>
<td>New</td>
<td>New</td>
</tr>
<tr>
<td>Packet Data Switching Node (PDSN)</td>
<td>New</td>
<td>New</td>
</tr>
</tbody>
</table>

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

5. Modeling

Using the real option model, 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). Recall the following from Section 2:

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

where

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

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

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

\[
T = \left( \sigma^2 - 2\rho \sigma \delta + \delta^2 \right)
\]

To calculate \( H \), the option value of the chosen transition scenario, the model uses three variables, \( B \) (the value of the new technology), \( P \) (the value of the old technology), and \( T \) (cumulative uncertainty). Wireless market share is used as the value of \( B \) and \( P \) because the technology value is proportional to market power (i.e., market share). Cumulative uncertainty \( (T) \) is the combined uncertainty of the two technologies being compared. Technological uncertainty is the volatility of the underlying technology value (i.e., market share). For estimating the uncertainty (volatility) of technology value, the historical number of subscribers was used. The volatility of technology value is applied to the concept of
compound return\(^1\) and the standard deviation (STD) metric. The first step is to calculate the compounded return of the technology value.

\[
\mu_t = \ln(V_t / V_{t-1})
\]

where \(\mu_t\) is the compound return of technology value between \(t\) and \(t-1\)

\(V_t\) and \(V_{t-1}\) are the number of subscribers in time \(t\) and time \(t-1\)

The next step is to calculate the uncertainty (\(\sigma\)) of technology using the standard deviation formula.

\[
\sigma = \sqrt{\frac{1}{(n-1)} \sum (\mu_i - \bar{\mu})^2}
\]

The two transition scenarios are: (1) *inter-generational technology transition*, and (2) *intra-generational technology transition*. The inter-generational scenario deals with three cases: Analog-to-TDMA, Analog-to-GSM, and Analog-to-CDMA, while the intra-generational scenario also deals with three cases: TDMA-to-GSM, TDMA-CDMA, and GSM-to-CDMA.

### 5.1 Assumptions, Scenarios, and Procedure

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

- First, it is impossible for a firm to migrate to older technology (backward migration). That is, a firm always prefers new technologies instead of old technologies.
- Second, a firm can only one technology when it decides to migrate.
- Third, there is no limitation on technology choice. At present, GSM is standardized in Europe, but we allow a firm to choose any technology (like the US).

Based on these assumptions, the following are the technology migration paths. The scenario will start with an analog technology based in the year 1992.

- 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

\(^1\) The compounded return equals the logarithm of 1 plus interest rate. For example, if the return rate = 0.1 or 10%, then the compounded return is \(\ln(1+0.1) = 0.0953\).
• Scenario 16: Analog => cdma2000

Simulations are implemented as the following two steps.
• First, only one step in the migration path is calculated.
• Second, this value is combined with previously calculated values to get the value of the whole migration path.

5.2 Data

Since the aim of this study is to understand how our real option model 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 have made numerous experiments in which real data to identify the model’s parameters, and next the simulation results were analyzed to explain current situations. We hope to refine and enrich these data in future research.

Figure 7 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 should be largely phased out after 2004 in the US wireless market.

![Figure 7: Wireless Market Size](image)

Based on the number of subscribers in generation (Figure 7), Figure 8 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.
6. Results Analysis

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.

As indicated in the header of each of the subsequent graphs, the underlying data may be based either on the US market or on the worldwide market. With a suite of different technologies in use, the US market offers an interesting laboratory to test the real options approach. But the consequences are also real, as Cingular and AT&T Wireless discovered in 2002 as they each independently needed to determine their migration path away from the TDMA standard.

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

The first scenario is to move from Analog to TDMA in the US. Figure 9 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 9: The Value Curve of Technology Transition (Analog to TDMA)

Figure 10 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. GSM lags TDMA in Figures 9 and 10 because GSM was a later entrant in the US market.

Figure 10 The Value Curve of Technology Transition (Analog to GSM)

Moving from Analog to CDMA network technology is similar to TDMA, except that the magnitude of the option values are different (Figure 11). CDMA is rapidly growing in the US market, which is the reason for this result. Considering figures 9-11 together, we see the story behind the transition to 2G; we also see the sensitivity of this technique to the market data that are used.
6.2 Intra-Generational Technology Transition (2G=>2G)

The next scenario (Figure 12) 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 and Cingular. The reason for this is evident by looking at NOV based on world data instead of US data (Figure 13). In this figure, there is great value in an intra-generational transfer; one, in fact, beginning earlier than what AT&T Wireless and Cingular actually did.
Another 2G scenario (Figure 14) 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 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.
6.4 Towards 3G

Figure 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.
The next scenario (Figure 17) 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 17: CDMA-cdma2000 Scenario (US)

6.3 Summary of the Results

Figure 18 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.
7. Concluding Remarks

In this paper, we developed a theory to assess the transition (replacement) from old technology (premium value) to new technology (option value). We also have discussed the evolution of wireless network technologies as a case study to apply our model in the US.

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.

The result shows that the evolution of wireless network technologies between generations is desirable, but not desirable in case of the transition 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 this preliminary model and practice of real options, 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?

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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