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Technology forecasting for wireless communication

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Abstract

Wireless communications technologies have undergone rapid changes over the last 30 years from analog approaches to digital-based systems. These technologies have improved on many fronts including bandwidth, range, and power requirements. Development of new telecommunications technologies is critical. It requires many years of efforts. In order to be competitive, it is critical to establish a roadmap of future technologies. This paper presents a framework to characterize, assess and forecast the wireless communication technologies. A DEA-based methodology was used for predicting the state-of-the-art in future wireless communications technologies.
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Keywords: Technology forecasting; Data envelopment analysis; Wireless communication

1. Literature review

There are many techniques that can be used to develop technology forecasts. Linstone (1999) provides an overview of methods evolving over time. Other researchers including Ayres (1999), Martino (1999) and Porter (1999) also provide comprehensive treatments of many approaches. Technology forecasting can be done both qualitatively as well as quantitatively. Linstone (2003) and du Preez and Pistorius (2003) provide examples of qualitative approaches such as multiple perspectives and threat/opportunity analysis which help to dissect problems so that further analysis can be done with quantitative models. Fildes (2006) provides an excellent review of forecasting research and outlets for publications. De Gooijer and Hyndman (2006) add to this research by focusing on time series forecasting. Meade and Islam (2006) provide a similar in-depth analysis for innovation diffusion.

The Technology Futures Analysis Methods Working Group (Porter et al., 2004) provides a good review of integrating multiple methods and evolving new methods for technology forecasting. Methods used frequently include scenarios (Sager, 2003; Silberglitt et al., 2003; Winebrake and Creswick, 2003), Delphi (Rowe and Wright, 1999), Growth Curves (Modis, 1999; Devezas et al., 2005), Analogies (Barley, 1998) and Innovation Diffusion Forecasting (Ilonen et al., 2006). Emerging methods include use of DEA (Anderson et al., 2002; Inman et al., 2006), Evolutionary Theory (Bowonder et al., 1999), Technology Roadmaps (Phaal et al., 2004), Patent Analysis (Kayal, 1999), Bibliometric Analysis (Watts and Porter, 1997; Daim et al., 2006), and Back Propagation Network (Wang and Shih-Chien, 2006). Kumar et al. (2002) indicate the necessity of combining the forecasting model with the perceived future industry dynamics. He emphasizes that the quantitative forecasting methods such as time series and econometric modeling have become less accurate and cannot be relied upon because the industry no longer has the stable historical relationship that these models rely on. The literature suggests that including forecasts from different statistical methods generally improves accuracy when significant trends are involved. Useful information can be obtained using several sources of forecasts, adjusting for biases. Yoo and Moon (2006) suggest that instead of trying to choose the best single method, one should combine the results from different methods, which would help in reducing errors arising from faulty assumptions, biases, or mistakes in the data.

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The new product development literature is relevant because the efforts to create these new technologies are relatively similar to product development and it will provide technology platforms upon which other products will be developed. There is an extensive literature on new product development but for the sake of providing a context and linkage to this literature, we will provide a discussion of a few select papers. The importance and usefulness of this work can be demonstrated in a survey by G.M. Scott of technology management practitioners concerning new product development (Scott, 1999). Scott ranked the 24 most significant management of technology problems in new product development. The top six problems identified by practitioners were

(1) Strategic planning for technology products
(2) Technology core competencies
(3) Creating a conducive culture
(4) New product project selection
(5) Cycle time reduction
(6) Technology trends and paradigm shifts

This paper has a clear link to four of these six most important new product development problems (1, 4–6) faced by practitioners.

First, Moore's Law has been an important part of the long-term strategic plan of microprocessor companies as evidenced by the billions of dollars spent on manufacturing facilities for each new generation of microprocessors and the roadmaps of Sematech. Similarly, this approach can be used to develop estimates of future performance from past performance trends to assist in longer range product planning.

The connection between this work and the problem of *new product project selection* is clear in the domain of these types of rapidly evolving products. Using estimates of technical progress, a project can be evaluated against how it performs relative to this future level of performance. The estimate of rates of product performance change can be used to provide a clearer product performance goal early in the development stage.

As noted by Gupta and Wilemon (1990), problems with product definition were the leading cause of delayed projects. Improvements in this area will help in *cycle time reduction*.

The work in this paper is particularly well suited to examining *technology trends and paradigm shifts*. The annual technology change directly estimates measure trends. Also, it may be possible to recognize the impact of disruptive technologies such as the digital light processor technology of Texas Instruments on the computer display projector market by seeing sudden changes in the efficiency frontier or rate of change. In this way, a disruptive technology may initially appear to occupy a small niche, but as this new technology is refined, it becomes standard practice and occupies a larger portion of the frontier. This study attempts to estimate future demand for wireless technologies and evaluate the service. To this end, Technology Forecasting using Data Envelopment Analysis (TFDEA) method will be used in addition to other supplemental methods. In the last few years, the mobile industry has been planning on the launch of communication technologies beyond third generation (3G).

Nunno (2003) claims that the demand for more robust mobile networks will increase even after deployment of 3G. Some characteristics of the next generation of mobile service are expected to be a greater global compatibility, a greater bandwidth and robust securities for emergent mobile-commerce applications (Nunno, 2003). Rappaport (2001) indicates in his book that the most important future process for the wireless communication will be its standardization. Table 1 provides a list of literature, the technology forecasting methods used and the results for the forecasting of future wireless technologies.

2. Methodology

One of the key methods used in this report is Data Envelopment Analysis (DEA). The approach of DEA has been used in comparing telecommunication systems and countries frequently; for example, see Majumdar and Chang (1996), Sueyoshi (1998), Cooper et al. (2001), Lien and Peng (2001), and Uri (2001). In contrast, this work uses a recently developed extension of DEA called TFDEA to predict future state-of-the-art technologies. This is the first time TFDEA has been applied to wireless communication systems. TFDEA was created in 2001 as an alternative quantitative approach for technology forecasting. It has been applied to a number of industries to lend insight to managerially relevant issues. In the case of enterprise database systems (Anderson et al., 2001), it was able to empirically identify the potentially disruptive technology of open source software upon the traditional database software industry. Another application showed how Moore's Law could be extended to multiple dimensions in the case of microprocessors (Anderson et al., 2002). The latter paper, by Inman, Anderson, and Harmon, formalizes the linkage to the technology forecasting literature by rigorously comparing TFDEA to a previously published influential paper (Martino, 1993; Anderson et al., 2002) and model for technology forecasting. The TFDEA approach was found to provide both a managerially and statistically significant improvement over the previously published technology forecasting results.

TFDEA uses the concept of state-of-the-art (SOA) in conjunction with DEA to determine historical levels of technology and determine trends in order to assess future technological characteristics. SOA is determined through analysis of products that implement a particular technology at a given point in time. The SOA is defined (Sahal, 1976) as "the state of best implemented technology as reflected by the physical and performance characteristics actually achieved during the time period in question." TFDEA improves on previous SOA approaches by

Table 1
Research focusing on forecasting wireless technologies

Literature	Technology forecasting method	Description	Result
Lee (2000)	Estimation	Future of 3G	Potential spectrum congestion and deficiency of the existing 3G standard around 2007–2010; serious network traffic of the existing mobile standards around years 2010–2015
Kumar et al. (2002)	MSHARE	A multi-component model (two-phase process)	Uses secondary data (from secondary sources) as well as primary data (from the ring down methodology and purchase intentions surveys)
Venkatesan and Kumar (2002)	Genetic algorithms	Provide predictions of category sales, time of peak sales and sales at the peak of cell phones	Slowdown in growth in the wireless phone market is a long-term phenomenon in the seven EU countries. Firms should focus on newer and useful innovations
du Preez and Pistorius (2003)	Analysis method	Political, economic, social and technological	Support an assessment of the impacts of developments on the organization
Frank (2004)	Logistic model	Uses the data on wireless subscribers in NMT and GSM to study the diffusion of wireless communications in Finland	Economic situation has affected the relative growth rate, and that the wireless network coverage has affected the number of potential adopters—penetration rate will be about 91.7% in 2009
Yoo and Moon (2006)	Contingent valuation	Assessing the future demand for new technology in the early stages of development or adoption	Reasonable method for future demand estimation

avoiding the fixed tradeoffs and central tendencies associated with regression analysis (Martino, 1992). This is done by using DEA, which is an econometric methodology for measuring relative efficiency built upon the foundations of Debreu (1951), Koopmans (1951), and Shepherd (1970). Since its original formulation in 1978 by Charnes et al. (1978), DEA has been widely employed for a variety of purposes in over 2000 research papers (Cooper and Seiford, 2004). In this work, we will use DEA to form a technology index of products relative to the SOA.

3. Technology characterization

Different technologies and systems for cellular mobile telecommunications have been developed with the start of the communications era. There are several technical features for the classification. The first distinguishing factor among the systems is the way the signals are transmitted: *analog*, radio waves varying in frequency and amplitude; *or digital*, having a stream of discontinuous pulses that correspond to the digital bits used in computers (Rappaport, 2001; Gruber, 2005). A second important way to distinguish cellular systems according to Gruber (2005) is by the "access mechanism." The spectrum is divided into frequency bands, referred to as channels, which are then allocated to the different users. Considering the way channels are allocated, three different mechanisms can be distinguished: frequency division multiple access (FDMA), time division multiple access (TDMA) and code division multiple access (CDMA).

As a third measure, Gruber (2005) and Rappaport (2001) classify cellular mobile systems by generations, which is widely done in the communications industry. The first generation of wireless technologies is analog systems, consisting of devices which have a military/defense origin. In the second generation, all the standards are commercial centric and they are digital in form. Later on, to meet the growing demands in the number of subscribers (increase in network capacity), rates required for high speed data transfer and multimedia applications, the third generation standards started evolving. The systems in this standard are basically a linear enhancement of 2G systems (Gruber, 2005).

Fourth generation (4G) could be defined as a network based on the Internet and other applications and technologies such as Wi-Fi and WiMAX. Taking this into consideration, it can be expected that 4G is not going to be just one defined technology or standard, but a compatible combination of technologies and protocols to enable the highest throughput and lowest cost. Table 2 summarizes the evolution of generations of wireless technologies and their important characteristics. Important underlying technical designs included moving from an analog way of transmitting signals to digital and from circuit switched to packet switched. Each subsequent generation has been getting more complex and demanding in its evolution, but each innovation is built upon the previous technologies. The following section will review the wireless technologies and their parameters, which will lead to the table used for the TFDEA analysis. At first, a description will be given for the wireless technologies used, which will be followed by the parameters taken into account for analysis.

3.1. First generation analog

First generation (1G) wireless telephone technology is an *analog* cellphone standard that was introduced in the 1980s

Table 2
Characteristics for wireless technologies by generation (Bernard, 2003)

Generation			
1G	2G	3G	Beyond 3G
Analog	Digital	Digital	Digital
Circuit switched	Circuit switched	Packet and circuit switched	Packet switched
Basic voice telephony	Voice plus basic data applications	Data and multimedia applications	All IP based
Low capacity	Low data speed	Medium data rates	More advanced multimedia applications
Advanced mobile phone service	CDMA, PDC, GSM	WCDMA, CDMA2000, TD-SDMA	OFDM, Multi Carrier CDMA
Limited local ad regional coverage	Enhancements toward packet-switching, higher data rates	Global coverage	Global coverage
	Transnational and global roaming	Global roaming	Global roaming
			High speed data
			Improved QoS
			User in control
			Flexible platform of complementary access systems

Table 3
First generation protocols (analog)

Generation	Technologies	Multiple access method	Adoption by country	Year of first commercialization
1G	Nordic Mobile Telephone 450 (NMT-450)	FDMA	Nordic countries, Switzerland, the Netherlands, Eastern Europe, Russia	1981
	Nordic Mobile Telephone 900 (NMT-900)	FDMA	Nordic countries; Switzerland, the Netherlands, Eastern Europe, Russia	1986
	Advanced Mobile Phone Service (AMPS)	FDMA	USA, then worldwide	1983
	Total Access Communications System (TACS)	FDMA	UK, Italy, Spain, Austria, Ireland	1985
	Narrowband Analog Mobile Phone Service (NAMPS)		USA, Israel	1993

until being displaced by 2G *digital* cellphones. Table 3 gives an overview of the 1G technologies with their year of commercialization. Some technologies within the 1G are Advanced Mobile Phone Service (AMPS), Total Access Communications System (TACS) and Narrowband Analog Mobile Phone Service (NAMPS).

Analog cellular service, which imposes cost and spectral inefficiencies, is scheduled to end in 2007. Analog cellular technology has been largely replaced by digital technology.

3.2. *Second generation digital*

The second generation (2G) wireless systems were initiated mainly for voice applications and to support circuit-switched services. Table 4 gives an overview of the 2G technologies. As seen in the table, different access methods are being used for each technology such as TDMA, FDMA and CDMA.

3.3. *Third generation digital*

3G systems have been designed for both voice and data. Initially, the goal was to achieve a single global standard for the 3G era (UMTS), but later on the European GSM was challenged by the CDMA technology. An overview of these systems can be seen in Table 5.

3.4. *Fourth generation*

4G is short for fourth generation. The WWRF (Wireless World Research Forum) defines 4G as "a network that operates on Internet technology, combines it with other applications and technologies such as Wi-Fi and WiMAX, and runs at speeds ranging from 100 Mbps (in cell-phone networks) to 1 Gbps (in local Wi-Fi networks)" (Kim et al., 1999). To provide the highest throughput and lowest cost, 4G will combine the technologies and protocols accordingly.

Table 4
Second generation protocols (digital)

Generation	Technologies	Multiple access method	Adoption by country	Year of first commercialization
2G	Digital AMPS (D-AMPS, IS-54, TDMA)	TDMA/FDMA	United States and Canada	1990
	Personal Digital Cellular (PDC)	TDMA/FDMA	Japan	1993
	Code Division Multiple Access (CDMA One)	CDMA/FDMA	North America, Korea, other Asian countries	1995
	Global System for Mobile communications (GSM)	TDMA/FDMA	Worldwide (212 countries)	1992
	Digital Cellular System 1800 (GSM 1800)	TDMA/FDMA	Europe and Asia Pacific	1992
	Integrated Digital Enhanced Network (iDEN)	TDMA	North America initially; Korea, China, South America to follow	1994
2.5G	CVDMA2000 1XRTT	CDMA	Korea first then USA and Japan	2001
	GPRS	TDMA	An upgrade for GSM networks	2001
	EDGE	TDMA	An upgrade for HSCSD/GPRS capable GSM network	2001

Table 5
Third generation protocols (digital)

Generation	Technologies	Multiple access method	Adoption by country	Year of first commercialization
3G	WCDMA (or UMTS)	CDMA	Korea, Japan, Europe, USA and other Asian Countries	2001
	CDMA2000 $1\times$EV	CDMA	Same as CDMAOne plus South America, Australia, India, China, Russia, and Some African Countries	2004
	HSDPA (TD-SCDMA)	TDMA/CDMA	China	2007
	HSUPA	TDMA/CDMA	USA, Europe, and Japan initially	2007
	OFDM/OFDMA			

Ohmori et al. (2000) suggest that the 4G-cellular systems should not only be high-speed but also high-capacity, with low-bit cost and the ability to support the services needed for 2010 and beyond. In order to achieve the high capacity with reasonable frequency bandwidth, Ohmori et al. (2000) expect that the cell radius of 4G-cellular systems shall be decreased from that of present cellular systems. However, current cellular radio access network (RAN) structures are not optimized for microcellular networks. Thus, a new revolutionary RAN structure with reduced bit cost will be an industry challenge for the coming years (Ohmori et al., 2000).

OFDM (Orthogonal Frequency Division Multiplexing) and OFDMA (Orthogonal Frequency Division Multiple Access) are candidates for the access technologies for the 4G in order to better allocate network resources to multiple users. 4G devices could use SDR (software-defined radio) receivers, allowing better use of available bandwidth as well as making use of multiple channels simultaneously (Ohmori et al., 2000).

Ohmori et al. (2000) suggest the following candidate future generation wireless systems: Multimedia Mobile Access (MMAC), Intelligent Transport Systems (ITSs) and High Altitude Stratospheric Platform Station Systems (HAPS) systems.

4. Technology assessment

Recent mobile phones include various services which were not available in the past generations such as emailing, web-browsing, music and movie playing, etc. Lee (2006) suggested four categories to evaluate performance of cellular systems such as voice quality, data quality, picture/vision quality and service quality. While these four performance factors help to evaluate overall service of a cellular system from the user perspective they are largely a function of many factors beyond just the wireless technology to be forecasted. These factors include the coder/decoders, (codecs), used for sound and video, handset design, etc. For the sake of this paper, we will limit the technology forecast to the data transmission capability.

The current wireless radio communication systems consist of several kinds of wireless systems, from simple cordless phones to mobile cellular systems and personal communication systems. These different radio communication systems share some common characteristics. Arguably, the most basic differences among the technologies are the area covered by a base station and the speech quality. The fundamental object of wireless communication systems is to provide communication channels between a mobile radio station and a radio port or base station which connect users to the fixed network infrastructure through electromagnetic waves. Therefore, the major design factors are capacity, cost of implementation, and quality of service (Gibson, 1996).

The wireless technologies discussed in the previous sections have been developed to increase the capacity of wireless systems while keeping a certain required service quality. Therefore, the capacity of wireless communication is a very important factor for forecasting wireless communication systems.

The capacity of wireless systems is closely related to frequency usage. The frequency spectrum on which wireless communication equipment depends is a limited resource. A major problem of the radio communication system is the limitation of the available radio-frequency spectrum because of high demand with limited spectrum. Therefore, the ideal mobile system can be defined by a system operating within a limited assigned frequency band and serving an almost unlimited number of users (Lee, 2006). Key technology characteristics to improve the capacity include the channel bandwidth, information compression, variable bit-rate control, improved channel assignment algorithms, and a selection of multiple access schemes (Garg, 2001). These factors can be reflected in forecasting models directly or indirectly.

The most common measure of the capacity is spectral efficiency. A good measure of spectral efficiency helps one to estimate the capacity of a mobile communications system and allows one to set up a minimum standard as a reference of measure (Garg, 2001). Therefore, some important metrics used for measure of spectral efficiency can also provide representative performance features of a wireless technology, and hence good variables for our forecasting model. Spectral efficiency can be generalized as follows:

$$\text{Spectral efficiency} = \frac{\text{Total number of channels available in the system}}{(\text{Bandwidth})(\text{Total coverage area})}.$$

Both the total number of channels and bandwidth are selected as key factors for our forecasting model. The total coverage area is excluded in this study because this factor is difficult to measure consistently across generations and is frequently specific to the particular implementation decisions of carriers. This leaves three remaining parameters affecting spectral efficiency: channel bandwidth, number of channels, and channel bit rate. The channel bit rate is included in the model since it is an important technical performance parameter even though it is not explicitly included in the spectral efficiency formula.

Table 6
Parameter characteristics

Parameter	Definition	Metrics
Channel bandwidth	Channel spacing, RF channel spacing or bandwidth per channel Example: GSM Frequency band: Base station: 935–960 MHz, Mobile station: 824–849 MHz Bandwidth = 960–935 = 824–849 = 25 MHz Bandwidth = channel width × number of channels	KHz
Number of channels	A channel is a communications path between two computers or devices. Most commonly a channel describes a pair of radio frequencies, one to receive on and one to transmit. In a digital discussion, a channel is also a communication path within a data stream. Voice traffic is digitized and put within the digital traffic channel. (*Source*: Tom Farley, "Cellular Telephone Basics", Retrieved from http://www.privateline.com/mt_cellbasics)	Number
Channel bit rate	The channel bit rate is the channel transmission bit rate for digitally modulating the carrier and is also called the "transmission rate" or "symbol rate/chip rate"	Kbs
Transmission power	Maximum power required to transmit signal	MW
Number of speech channels	Number of users that can simultaneously access/use a channel	Count
Data capacity	Signaling transfer speed per user	Kbs

In addition to the three spectral efficiency related parameters which are used as major factors in the TFDEA model, other important technical parameters such as trends in transmission power, number of speech channels, and data capacity will be discussed along with their trends with respect to expected future technological progress. The detailed definitions of all parameters which are used and adopted in this study are provided in Table 6.

Twenty technologies and their six parameter values are used in this study as well as the year of first commercialization. Data were gathered from various sources such as books, articles, and Internet websites. Since some sources are using different metrics or different concepts with the same name, validation has been done by comparing the information with multiple sources. For unclear definitions and metrics, we validated data through informal interviews with engineers in three major companies in the mobile communication industry. However, a more concrete and complete data set would aid further study. The data set used in this study is provided in Table 7.

5. Technology forecasting

This analysis is based on an extension of spectral efficiency. We examined the changing bandwidth require-

Table 7
Data set used in this study (Boucher, 1992; Hammuda, 1995; Garg and Wilkes, 1996; Gibson, 1996; Gruber, 2005; Lee, 2006)

Technology	Country adopted the technology	Multiple access method	Year[a]	Channel band width (kHz)	Transmission power (mW)	Number of speech channel per RF channel	Number of channels in the frequency band	Data capacity per user (kbs)	Channel bit rate (kbs)
NTT	Japan	FDMA	1979	25	–	1	600	0.3	0.3
NMT-450	Nordic countries; Switzerland, the Netherlands, Eastern Europe, Russia	FDMA	1981	25	15000	1	200	1.2	1.2
NMT-900	Nordic countries; Switzerland, the Netherlands, Eastern Europe, Russia	FDMA	1986	12.5	3000	1	1999	1.2	1.2
C450	Germany, Austria, Portugal, South Africa		1985	20	–	1	222	5.28	5.28
AMPS	USA, then worldwide	FDMA	1983	30	3000	1	666	10	10
TACS	UK, Italy, Spanish, Austria, Ireland	FDMA	1985	25	–	1	1000	8	8
CT2	Europe and Asia	FDMA	1991	100	10	1	40	19.2	72
DECT	USA, Europe	TDMA/ TDD	1993	1728	250	12	10	–	1152
TDMA	United States and Canada	TDMA/ FDMA	1990	30	600	3	832	9.6	48.6
PDC	Japan	TDMA/ FDMA	1993	25	–	3	640	9.6	42
CDMA	North America, Korea, other Asian countries	CDMA/ FDMA	1995	1250	600	15	20	14.4	1228.8
GSM	Worldwide (212 countries)	TDMA/ FDMA	1992	200	1000	8	124	14.4	270.833
JDC	Japan	TDMA/ FDMA	1991	25	–	3	640	14	42
DCS 1800	Europe and Asia Pacific	TDMA/ FDMA	1992	200	1000	8	374	9.6	270.833
iDEN	North America initially; Korea, China, South America to follow	TDMA	1994	25	–	6	600	9.6	64
CDMA2000	Korea first then USA and Japan	CDMA	2001	1250	–	30	64	153	1228.8
GPRS	An upgrade for GSM networks	TDMA	2001	200	–	–	124	128	270.833
EDGE	An upgrade for HSCSD/GPRS capable GSM network	TDMA	2001	200	–	–	195	384	812.5
WCDMA	Korea, Japan, Europe, USA and other Asia	CDMA	2001	5000	2000	196	12	364	5760

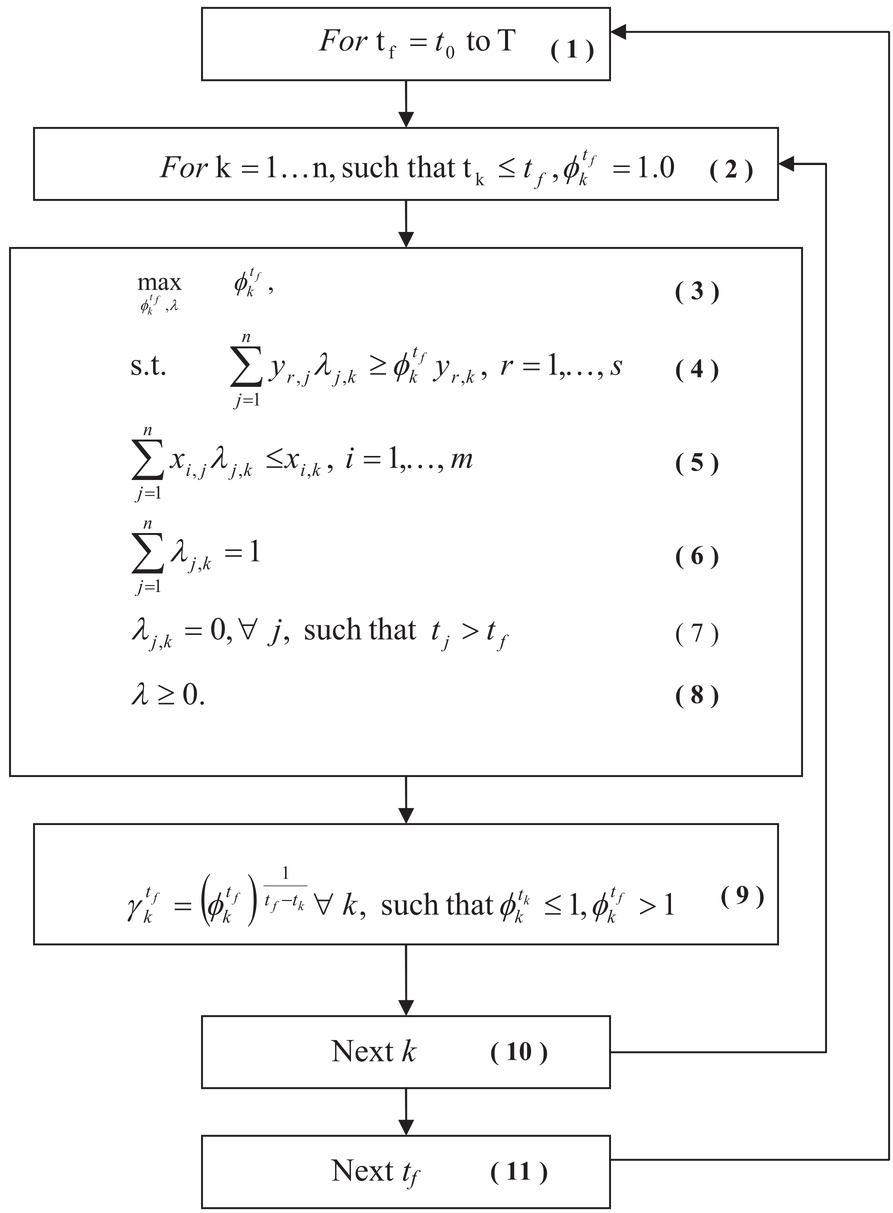
[a]The first commercialized year is used.

ments and total data capacity for 20 telecommunications protocols developed between 1979 and 2001. The data is summarized in Table 8.

As discussed earlier, a variety of trends can be observed in the data including increased overall bandwidth for telecommunications protocols and increased total data capacity. Over time, increasing simple spectral efficiency is also apparent and iDEN has the highest spectral efficiency, which is consistent with the literature (Geiger et al., 1997; Hansen, 1998; Garber, 2002).

Next we applied TFDEA to this data set. The TFDEA approach allows for multiple inputs and multiple outputs, but in this application, we found the best model to be a straightforward one input, one output model. We used as an input the total bandwidth for all channels (measured in Megahertz) and as an output the total data for all channels as measured in megabits per second. TFDEA allows for different returns to scale assumptions. In this study, we used variable returns to scale, although increasing, decreasing, or constant returns to scale could also be used.

The TFDEA approach is mathematically summarized in Eqs. (1) through (11). The analytical core of TFDEA is an econometric technique called DEA developed Charnes et al. (1978). We used a simplified TFDEA approach relative to some earlier work by foregoing a variable frontier time denoted as $t_{\text{effective}}$ (or t_{eff}) in Inman et al. (2006). A detailed explanation and compelling validation of TFDEA in comparison to other technology forecasting approaches amount of additional output which should be achievable by technology k at time period t_f if it were state-of-the-art at that time. The variables, $\lambda_{j,k}$, describe how much of technology j is used in setting a target of performance for technology k.



can also be found in Inman et al. (2006). Conceptually, TFDEA calls for testing each technology, k, at each time period, t_f, against all technologies commercialized up to that time. Briefly, $x_{i,k}$ represents the ith input and $y_{r,k}$ represents the rth output of technology k. In the current study with its one input and one output model, this results in $m = s = 1$. The variables for the linear program underlying DEA are $\lambda_{j,k}$ and $\phi_k^{t_f}$. The variable $\phi_k^{t_f}$ also serves as the objective function and represents the

The first result is a comparison of each technology to all technologies available at that time and earlier. In these results as noted in Table 9, technologies with a score of 1.0 are considered efficient at time of first commercialization. Conversely, scores larger than one indicate the amount by which the output (total data capacity across all channels) should be increased relative to its input in order to be SOA in the year of its release compared to other available technologies.

A number of interesting conclusions can be drawn from the preceding table (Table 10). As we would expect, first

Table 8
Data used for TFDEA and the simple spectral efficiency score

	Short name	Year first commercialized	Input	Output	Simple spectral efficiency (Mbps/MHz)
			Bandwidth for all channels (MHz)	Total data all channels (Mbps)	
1	NTT	1979	15	0.18	0.01
2	NMT-450	1981	5	0.24	0.05
3	AMPS	1983	19.98	6.66	0.33
4	C450	1985	4.44	1.17216	0.26
5	TACS	1985	25	8	0.32
6	NMT-900	1986	24.988	2.3988	0.10
7	TDMA	1990	24.96	40.4352	1.62
8	CT2	1991	4	2.88	0.72
9	JDC	1991	16	26.88	1.68
10	GSM	1992	24.8	33.5833	1.35
11	DCS 1800	1992	74.8	101.292	1.35
12	DECT	1993	17.28	11.52	0.67
13	PDC	1993	16	26.88	1.68
14	iDEN	1994	15	38.4	2.56
15	CDMA	1995	25	24.576	0.98
16	TD-CDMA	2000	20	13.2	0.66
17	CDMA2000	2001	80	78.6432	0.98
18	GPRS	2001	24.8	33.5833	1.35
19	EDGE	2001	38	51.4583	1.35
20	WCDMA	2001	80	92.16	1.15

Table 9
Data used for TFDEA and the simple spectral efficiency score

k	Short name	Year first comercialized	Bandwidth for all channels (MHz)	Total data all channels (Mbps)	Simple Spectral Efficiency (Mbps/MHz)	Efficiency at time of release γ_k^{2001}
1	**NTT**	**1979**	**15**	**0.18**	**0.01**	**1**
2	**NMT-450**	**1981**	**5**	**0.24**	**0.05**	**1**
3	**AMPS**	**1983**	**19.98**	**6.66**	**0.33**	**1**
4	**C450**	**1985**	**4.44**	**1.17216**	**0.26**	**1**
5	**TACS**	**1985**	**25**	**8**	**0.32**	**1**
6	NMT-900	1986	24.988	2.3988	0.10	3.33361
7	**TDMA**	**1990**	**24.96**	**40.4352**	**1.62**	**1**
8	**CT2**	**1991**	**4**	**2.88**	**0.72**	**1**
9	**JDC**	**1991**	**16**	**26.88**	**1.68**	**1**
10	GSM	1992	24.8	33.5833	1.35	1.19682
11	**DCS 1800**	**1992**	**74.8**	**101.292**	**1.35**	**1**
12	DECT	1993	17.28	11.52	0.67	2.50143
13	**PDC**	**1993**	**16**	**26.88**	**1.68**	**1**
14	**iDEN**	**1994**	**15**	**38.4**	**2.56**	**1**
15	CDMA	1995	25	24.576	0.98	1.99044
16	TD-CDMA	2000	20	13.2	0.66	3.30746
17	CDMA2000	2001	80	78.6432	0.98	1.28799
18	GPRS	2001	24.8	33.5833	1.35	1.45032
19	EDGE	2001	38	51.4583	1.35	1.21631
20	WCDMA	2001	80	92.16	1.15	1.09908

technologies can be rapidly superseded by new technologies. While NTT's wireless protocol was SOA in 1979, as demonstrated by the efficiency score of one, it was immediately surpassed when the next technology was commercialized. To be SOA in 1981, it needed to achieve 33% more output (data capacity in megabits per second) for the same input (bandwidth in MHz) and by 1994, a SOA telecommunications protocol would achieve 212 times more output using the same bandwidth demands as NTT.

In contrast, some technologies continue to be deemed SOA for a range of years in terms of our spectrum efficiency. For example, CT2 was efficient at the time of first commercialization in 1991 and continued to be efficient relative to other technologies through 2001.

Table 10
Changing efficiency scores over time

k	Short name	Year first commercialized t_k	Efficiency at time of release $\phi_k^{t_k}$	$\phi_k^{t_f}$								
				1979	1981	1983	1985	1990	1992	1994	1995	2001
1	NTT	1979	1	**1**	1.33	25.1	27.2	119	138	213	213	213
2	NMT-450	1981	1		**1**	1	5.71	9.35	20.3	25.5	25.5	25.5
3	AMPS	1983	1			**1**	1	4.64	4.94	6.55	6.55	6.55
4	C450	1985	1				**1**	1	3.21	3.67	3.67	3.67
5	TACS	1985	1				**1**	5.05	5.06	6.11	6.11	6.11
6	NMT-900	1986	3.33361					16.9	16.9	20.4	20.4	20.4
7	TDMA	1990	1					**1**	1	1.21	1.21	1.21
8	CT2	1991	1						1	1	1	1
9	JDC	1991	1						1	1.47	1.47	1.47
10	GSM	1992	1.19682						1.2	1.45	1.45	1.45
11	DCS 1800	1992	1						**1**	1	1	1
12	DECT	1993	2.50143							3.54	3.54	3.54
13	PDC	1993	1							1.47	1.47	1.47
14	iDEN	1994	1							**1**	1	1
15	CDMA	1995	1.99044								1.99	1.99
16	TD-CDMA	2000	3.30746									3.31
17	CDMA2000	2001	1.28799									1.29
18	GPRS	2001	1.45032									1.45
19	EDGE	2001	1.21631									1.22
20	WCDMA	2001	1.09908									1.10

Table 11
Technological rate of change

k	Short name	Year first commercialized t_k	Efficiency at time of release $\phi_k^{t_k}$	Efficiency relative to 2001 state-of-the-art ϕ_k^{2001}	Annual rate of change
1	NTT	1979	1	213	1.27605
2	NMT-450	1981	1	25.5	1.17568
3	AMPS	1983	1	6.55	1.11008
4	C450	1985	1	3.67	1.08464
5	TACS	1985	1	6.11	1.11982
7	TDMA	1990	1	1.21	1.01738
9	JDC	1991	1	1.47	1.03912
13	PDC	1993	1	1.47	1.04913
				Average	1.10899

The aforementioned measurements of how the technology is surpassed over time can be used to estimate a rate of technology change. For this we will use the year 2001 values of technology being surpassed but which had been SOA at time of release to calculate the amount by which wireless technology had progressed. In other words, what annual rate of change would be needed to explain the amount by which a previously SOA technology had been superceded by 2001. Table 11 lists the eight technologies which were state-of-the-art (efficient) at time of release but were surpassed by future technologies. The average annual rate of change was 1.109, indicating that output data capacity for wireless technology protocols increased by about 10.9% per year for any fixed level of input (bandwidth).

The rate of change value can then be used to estimate future levels of technology performance for SOA technologies. Table 12 takes the year 2001 technologies and first multiplies their outputs (data capacity) by the efficiency scores to develop an efficient projection and then multiplies that by the rate of change raised to the power corresponding to the forecast year.

This forecast predicts that in order for successors to the CDMA-based technologies (CDMA 2000 and WCDMA) to be technologically state-of-the-art in 2011, they will need to support a data transmission capacity of 285 Mbps given the same 80 MHz bandwidth.

HSDPA is the first evolution of WCDMA released in 2006 (Rysavy, 2006). The total data capacity within the broadband of 1920–1980 MHz is 138.24 Mbps (Derksen et al., 2006). In other words, the data capacity for 60 MHz of bandwidth will be 138.24 Mbps. Our analysis has predictions for bandwidths of 38 and 80 MHz. They are 104.99 and 169.90 Mbps respectively for 2006. A simple calculation would show that our analysis is predicting 138.99 Mbps. The prediction is extremely close to the actual in 2006.

6. Discussion

There are several implications of the research findings for both theory and practice. From a theoretical perspec-

Table 12
Forecasts of future state-of-the-art performance

k		BW all channels (MHz)	Total data capacity (Mbps)	Efficiency relative to 2001 state-of-the-art ϕ_k^{2001}	2001 target data capacity	Future forecasts of total data capacity (Mbps)		
						2006	2011	2015
17	CDMA2000	80.00	78.64	1.29	101.29	169.90	284.99	431.06
18	GPRS	24.80	33.58	1.45	48.71	81.70	137.04	207.28
19	EDGE	38.00	51.46	1.22	62.59	104.99	176.10	266.36
20	WCDMA	80.00	92.16	1.10	101.29	169.90	284.99	431.06

tive, the paper expands the use of DEA in technology forecasting. The findings are also important for practice. TFDEA is application of DEA to technology forecasting and was developed at Portland State University. The methodology so far has been applied to microprocessors, fighter jets, enterprise data systems and USB drives. It is the first time it is applied to wireless communication technologies. As the methodology requires the identification of a product function, it also defines the critical input and output elements that makes a wireless communication technology efficient. The function defined provides a relationship among key technical specifications that the service providers or manufacturers have control over and the customer preferences. In this way the methodology provides quantification and prediction functions for the research in quality function deployment or house of quality. Another aspect of using TFDEA on wireless communication technologies is the service perspective. This is the first time TFDEA has been used for a service innovation and it proved useful in this case as well.

Our results will provide further research direction for technology forecasting. Many models in the literature focused on one parameter at a time. Our model provides a multi-dimensional view of performance. We believe the process utilized in this research can be generalized so that researchers can initially identify the major components of the technology under investigation. In the paper, this was accomplished by defining spectral efficiency. One can take this to a level where spectral efficiency equivalents are defined for different major group of technologies, thus defining a system of technology evaluation and forecasting that can be used for almost any application. One other expansion of our model would be to monitor different technologies over time and try to capture changes in the efficiency model which may be good indicator for the presence of disruptive technologies. Continuous monitoring may enable us to predict the arrival of disruptive technologies.

Product development is one area that would benefit from this type of analysis. A range of performance parameters forecasted into the future will help validate design targets for products driven by new technologies. Typical R&D projects have high uncertainty in the beginning. The uncertainty ranges from design targets to expected performance. Although we may not necessarily help with expected physical performance, we may help reduce the uncertainty in the targeted range. The process can also be expanded to include other elements such as resources, expenses and other constraints to help us to assess whether or not we are getting more or less efficient in developing products. The phases where this will be most efficient would be the early phases. These are sometimes referred to as fuzzy front end of product development, where there is uncertainty about customer requirements and technology limits. So our approach can be a powerful tool to help reduce the fuzziness of the front end of product development.

Although the methodology provides good insight, decision makers should use this as a reference and combine it with other analyses being made, such as market and technology analyses. Recent wireless technologies have achieved similar spectral efficiency levels in the physical layer reaching to the theoretical limits with a focus on improving system performance (Rysavy, 2006). Therefore, comparing technologies of the same generation with a single measurement of spectral efficiency may not provide enough insight into when a new generation of technology will actually be adopted in a future market. While the methodology used in this paper provides how a specific technology will evolve over time based on a linear improvement in system performance, it will be vital to keep monitoring the market dynamics. For example, carriers may agree to choose to fully utilize the current infrastructure before they invest into a new one. These companies will most probably consider the adoption of any new technology to understand the optimal time to deploy the new technology. This type of market information could add value to the forecast for the wireless technologies. For this purpose additional analyses are recommended and they may include cost/benefit analysis and plotting growth curves of current and future generations.

7. Conclusions

The wireless technology industry has been rapidly evolving with dramatic technology changes. As the technology has advanced, development costs and times have increased, resulting in a greater need for insights regarding what the future holds. There has been a variety of both technology and market forecasts applied to the wireless technology.

This study examined past studies and applied a comprehensive approach including three steps, which are technology characterization, assessment and forecasting.

- *Step* 1 included a review of wireless technologies. Through this step, we identified the path of technology evolution. This helped us to identify which technologies and standards we were going to use for our analysis.
- *Step* 2 included a more detailed review of technical parameters that we were trying to assess and forecast. This phase resulted in a model and a set of variables to be used in our analysis. In this step we also conducted a forecast of the variables in the model independent of each other.
- *Step* 3 utilized a new approach, TFDEA for the first time in the wireless technology industry. It was found that a forecast of future performance could be developed and historical developments tracked. Future work could extend this model to incorporate additional inputs and outputs as well as additional wireless technology protocols.

The three-step process can easily be applied to other types of technologies, thus creating further technology forecasting opportunities.

The paper also included a limited validation where the forecasted performance was compared to the actual data. HSDPA, which is an advanced version of WCDMA released in 2006, has a total data capacity of 138.24 Mbps. Our model, built on historical data up until 2001, had indicated a data capacity of 138.99 Mbps for 2006.

Finally, this paper provides a group of future expansion of this research explained in the discussion part and summarized below:

(1) Developing further TFDEA models of other service innovations.
(2) Developing "spectral efficiency" equivalent for other technologies and related applications.
(3) Developing monitoring systems for predicting the arrival of disruptive technologies.
(4) Incorporating the approach into the front end of product development process to reduce the uncertainty. Case studies measuring improvements would be very useful.

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