# The Progress in Wireless Data Transport and its Role in the Evolving Internet

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## Abstract

The progress of wireless technology through the past 105 years is quantitatively reviewed in this paper. Spectral efficiency and coverage density are both found to increase in a relatively continuous exponential fashion over the entire period with spectral efficiency increasing at about 15% per year and coverage density at about 33% per year. Throughput by wireless technology was not found to follow a single exponential but instead followed an exponential with annual increase of only 5% up to the late 70s and since then (and the introduction of the cellular concept) has followed an exponential with annual increases of greater than 50%. These high rates of progress in the functional performance of wireless technology are an essential enabler for wireless interfaces to become the dominant mode for connecting to the Internet.

## Introduction

Quantitative study of technical progress has been pursued by many authors using a variety of approaches (1). While each of these efforts has its own methodological advantages and limitations, we are most interested in those that are useful in short term and longer term *quantitative understanding of the increase in technical capability*. Such studies allow one to understand the past and sometimes to cautiously extrapolate to probable (or possible) futures. The best known example of such a study was the work done by Moore (2) that has become known as Moore’s Law. The essence of this law is exponential increase with time (thus far without limitation) of the number of components on an integrated circuit and thus of the *functional* capability to perform computations per unit time and dollar. Recent work (3,4) that directly focuses upon long-term examination of functional capability has demonstrated exponential increases with time (essentially without limits) for a variety of progress metrics in different functional categories[1].

The key role of wireless data transport in the recent past, present and future of the Internet has been noted by various authors and discussed thoroughly by Kleinrock (5). Moreover, the many improvements in this technical capability have been discussed by many observers (6, 7) Nonetheless, there has been to our knowledge no published quantitative study of the progress that has been achieved over the long term. Indeed, a recent study (8) has examined the key technical changes in wireless over the past 30

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[1] The functional approach to quantitative study of technological progress is described more fully in the following two sections.

years utilizing a suite of technical forecasting tools and conclude that “a more concrete and complete data set would aid further study”.

The current paper utilizes the functional approach mentioned above for quantitatively studying technical capability. Data from the past 100 plus years are obtained and analyzed to quantitatively assess wireless progress from the viewpoint of three key Functional Performance Metrics. In order for wireless information transportation to play its role in the Internet infrastructure, the margin between the capability of wired transmission of information and wireless transmission must be limited and any gap in favor of wired transmission must not be increasing rapidly. If large gaps in performance exist or evolve, applications might emerge where wireless transmission would be unacceptable to users and over time with continued divergence, the use of wireless interfaces might face diminishing utility. Thus, one question examined in this quantitative assessment of wireless is its relationship over time relative to the technical capability of wired transmission of information.

# *Approach*

## The functional approach and past results

Recent research on quantification of the dynamics of technological development has utilized a *functional approach* (3, 4). This approach has allowed for the development of Functional Performance Metrics that apply to a wide range of functionally similar artifacts and has been applied to studying technological development in 6 categories for more than 100 years in each case. The essence of the functional classification system and the six categories studied are shown in **bold** type in Table I from Koh and Magee (4).

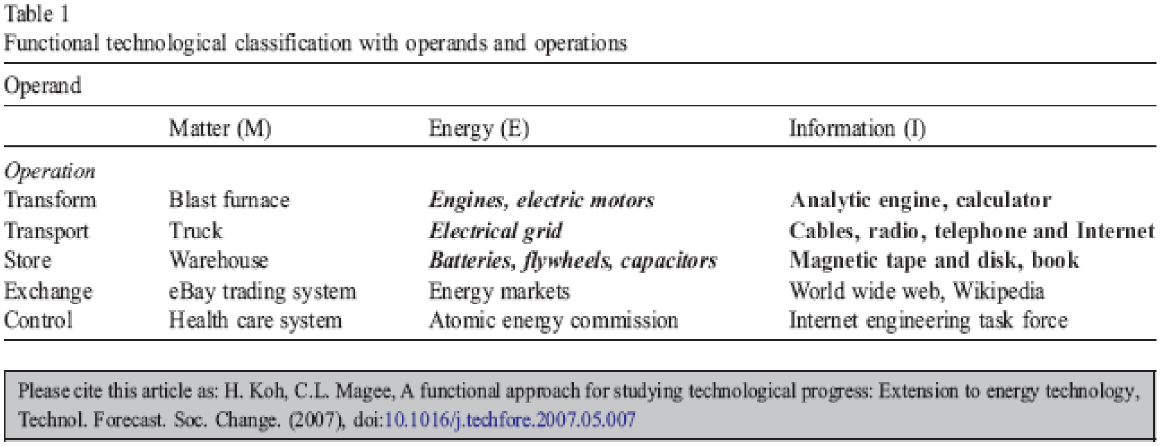

Table 1

Functional technological classification with operands and operations

| Operand | | | |
|---|---|---|---|
| | Matter (M) | Energy (E) | Information (I) |
| *Operation* | | | |
| Transform | Blast furnace | ***Engines, electric motors*** | **Analytic engine, calculator** |
| Transport | Truck | ***Electrical grid*** | **Cables, radio, telephone and Internet** |
| Store | Warehouse | ***Batteries, flywheels, capacitors*** | **Magnetic tape and disk, book** |
| Exchange | eBay trading system | Energy markets | World wide web, Wikipedia |
| Control | Health care system | Atomic energy commission | Internet engineering task force |

Please cite this article as: H. Koh, C.L. Magee, A functional approach for studying technological progress: Extension to energy technology, Technol. Forecast. Soc. Change. (2007), doi:10.1016/j.techfore.2007.05.007

In the two papers published by Koh and Magee, some key findings emerge that are important background for the further work reported here. These findings include:

- No persistent saturation effects are found in any functional category. Thus, the technical capability in none of the categories has been found to approach a limit. This clearly differentiates the technical capability (as measured in the functional approach) from technology diffusion studies long known to follow “S shaped” logistic curves (9).
- The technical capability follows exponential progress over the 100 plus year periods studied in all 14 FPMs examined covering both information and energy

technologies. Thus, prototype examples of such effects as Moore's law are greatly extended. The extension not only includes longer times but also that relatively continuous exponential progress is found for FPMs that involve multiple technology generations and breakthroughs. In the case of computation, the FPM is continuous with FPM data that includes analogue mechanical, vacuum tube and other computer technologies that pre-date the integrated circuit era foreseen by Moore (10).

- There is a very *significant range* of progress rates (3% to 35% annual change) depending on the functional category and in the case of energy technologies depending upon the particular technical approach being studied.
- The progress rates found for various information technologies have greatly exceeded those for energy technologies for the entire period studied (as far back as 150 years ago as shown for wired information transportation).

## Functional Performance Metrics for Wireless Technology

The present research extends the study of information transportation as the previous work essentially focused upon the undersea cable and other wired approaches in this functional category. Thus, we will be able to compare the results obtained in this paper with those previously obtained for wired transportation of information. This paper examines historical technological progress of wireless technology, using high-level, non-device specific performance metrics (FPMs). Arriving at appropriate and empirically obtainable FPMs is a major part of the work and the focus of this section.

In the functional category of information transportation, we chose to evaluate 3 aspects of wireless transportation that are among the most important performance characteristics for this category. In general, functional performance metrics [as described in (3)] are derived from specific *engineering tradeoffs* important in the domain of interest. The three FPMs specific to wireless technologies are summarized in the following table:

| Functional Category | Functional Performance Metric | Units |
|---|---|---|
| Wireless Transportation of Information | Throughput | Kbps |
| | Spectral Efficiency | bps / Hz |
| | Coverage Density | bps / $M^2$ |

Table 2: Wireless FPMs

The FPMs consider the *performance relative to some key resource* and thus explore engineering tradeoffs over time (3). In this case (as in most others), the FPMs are familiar figures of merit to engineers in the relevant field. In the first instance, *throughput* is of critical relevance for assessing wireless technological progress as time (determining the speed of transmission of a given amount of information) is always a relevant resource. Secondly, the *spectral efficiency* in wireless provides a good measure of the ability of the technology to make better usage of the limited resources of physical bandwidth contained in the radio spectrum. Radio spectrum is the single scarcest resource in the wireless telecommunications industry and it is therefore particularly relevant to explore the ability to transport increasingly larger amounts of information over this limited resource. And thirdly, using a *Coverage Density* FPM provides a metric of the ability of the technology to transport large amounts of information to ever higher numbers of people living in increasingly distributed areas.

## Data Sources and Data Quality

Since the performance of technological progress is measured with the FPMs described previously over the past 112 years, a great deal of attention was dedicated to the reliability of the historical data collected. The majority of the cases included measurements of performance for digital technologies for which accuracy can be presumed to be high. For those few cases of non-digital technologies, measurements from different sources where compared to validate their accuracy. In the case of the very old technologies like the Wireless Telegraph, only one source was identified. Moreover, the measurements at that time where established in words per minute and therefore a conversion formula was established to estimate the FPMs from the data found (See Appendix 1 for an explanation of this formula). Beyond this last issue, we conclude that the error margin is very low for the data collected.

The database created for the 3 Functional Performance Metrics defined for this study is given in Appendix I. A full set of data was collected from several sources from 1895 to 2007. Among the most important sources are the IEEE Xplore paper database and information obtained from publications from the International Telecommunications Union (ITU). Data has been collected for several wireless technologies that are frequently quoted as “standards” in the literature. Examples of such standards are GSM, CDMA and WiMax. The three functional performance metrics collected are (1) wireless throughput, (2) wireless spectral efficiency, and (3) wireless coverage density. In some cases, the data was found in the form of summary tables that contained data for several standards. However, in most cases the data had to be obtained in documents that described a particular standard in detail. Please refer to Appendix 1 for a detailed explanation on where and how the numbers for the database were finally obtained and how calculations were performed whenever needed.

Another issue that is important to discuss is the variation in the performance of the metrics identified due to the nature of wireless technologies. Wireless performance is dependent on factors such as weather, geographic conditions, mobile station characteristics, obstacles, and other factors that may influence the RF transmission environment. For the purpose of this study, we used the highest possible performance for every wireless standard identified. The data collected therefore represents an upper bound of the performance of such technologies and the reader should be advised that the performance could be significantly lower from the one presented in average RF environmental conditions. However, to assess the progress over time, it is best to consider a single condition and this is offered by looking at peak performance[2]. Moreover, when fitting the curves to the experimental data, we utilized only the dominant performances

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[2] This is consistent with the two papers of Koh and Magee (3,4)

and did not include systems that were introduced later and performed more poorly in the analysis as our goal is to characterize the progress of the leading technical capability.

## *Results*

### Wireless Throughput

The throughput data for wireless technology is plotted in Figure 1. A logarithmic scale was utilized in the graph to enable the observation of the progress made by the technology over the full time period (which a linear scale would not). It is evident in Figure 1 that the rate of progress has not been constant. Thus, fits over the two apparently different periods were made. Table 3 shows the statistical superiority for this two period approach. All of the models used were of the form y=b*exp(c*x).

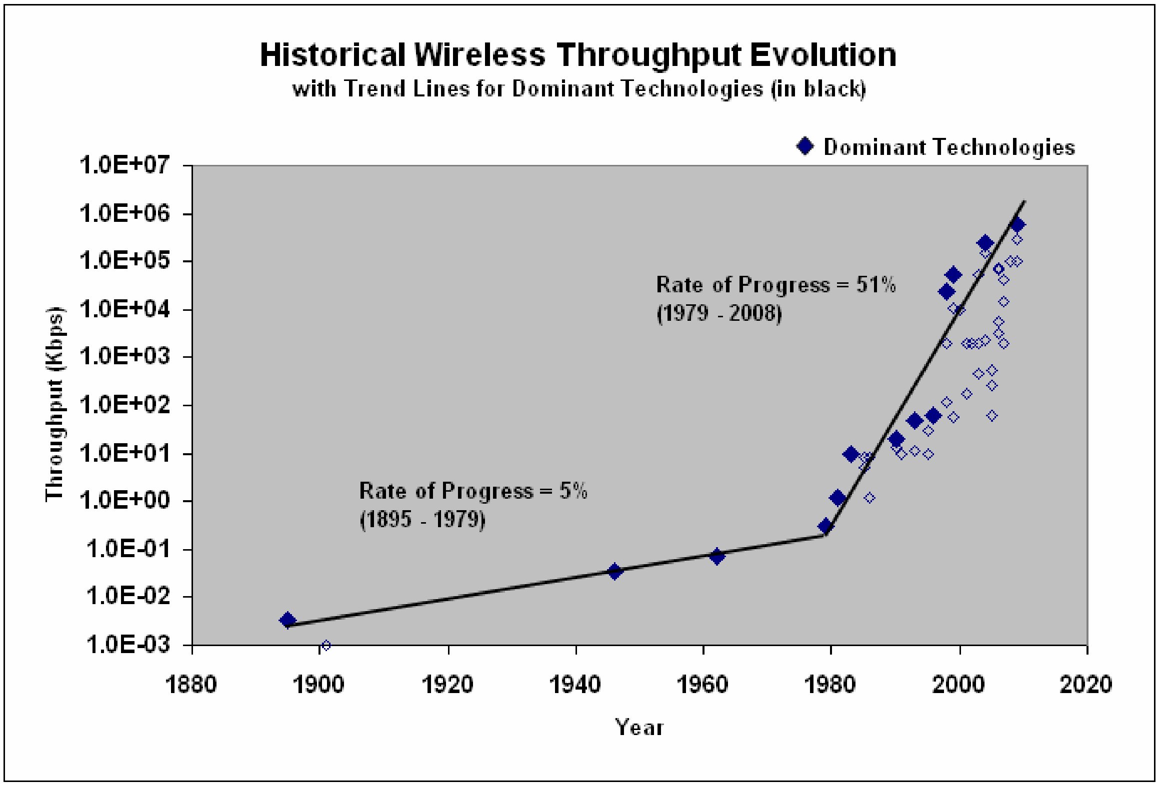

Figure 1: Wireless throughput FPM

Regression Analysis: Throughput FPM

| | Regression Equation | Progress Rate | Goodness-of-fit (R Square) | Significance Test (F-Test) Probability |
|---|---|---|---|---|
| Dominant Technologies (Full time period) | y=1E-05*exp(0.176*x) | 17.6% | 0.65 | 3.07E-04 |

| | | | | |
|---|---|---|---|---|
| Dominant Technologies (1895 – 1979) | y=2.8E-03*exp(0.0516*x) | 5.16% | 0.98 | 9.30E-03 |
| Dominant Technologies (1979 – 2009) | y=3E-20*exp(0.5124*x) | 51.2% | 0.91 | 6.19E-06 |

Table 3: Regression Results for throughput dataset

A rate of progress of 5% was obtained for the 1895-1979 range, while a rate of 51% was obtained for the 1979 – 2009 period.

The slow yearly progress during the first half of the 20th century is consistent with the fact that technological development was focused on making wireless voice transmission possible during this period. In contrast to the first phase, the development of the cellular concept in the late 70's clearly enabled the acceleration in the pace of progress of this FPM. The introduction of packet-switching technologies, together with the development of Wireless Local Area Networks in the 90's, may also have caused further acceleration but the statistical evidence is not as strong.

## Wireless Spectral Efficiency

Figure 2 exhibits the progress in spectral efficiency over the entire period again plotted on a logarithmic graph. The data exhibits a steady, almost constant, rate of progress throughout the full period of analysis and the fit to the exponential function is accordingly quite good (Table 3). Regression analysis shows both a very good goodness-of-fit and a highly significant F-test for the exponential model, namely, y=b*exp(c*x), where c represents the rate of progress and b represents a scale factor. The annual improvement rate over the entire period equals 15.5%.

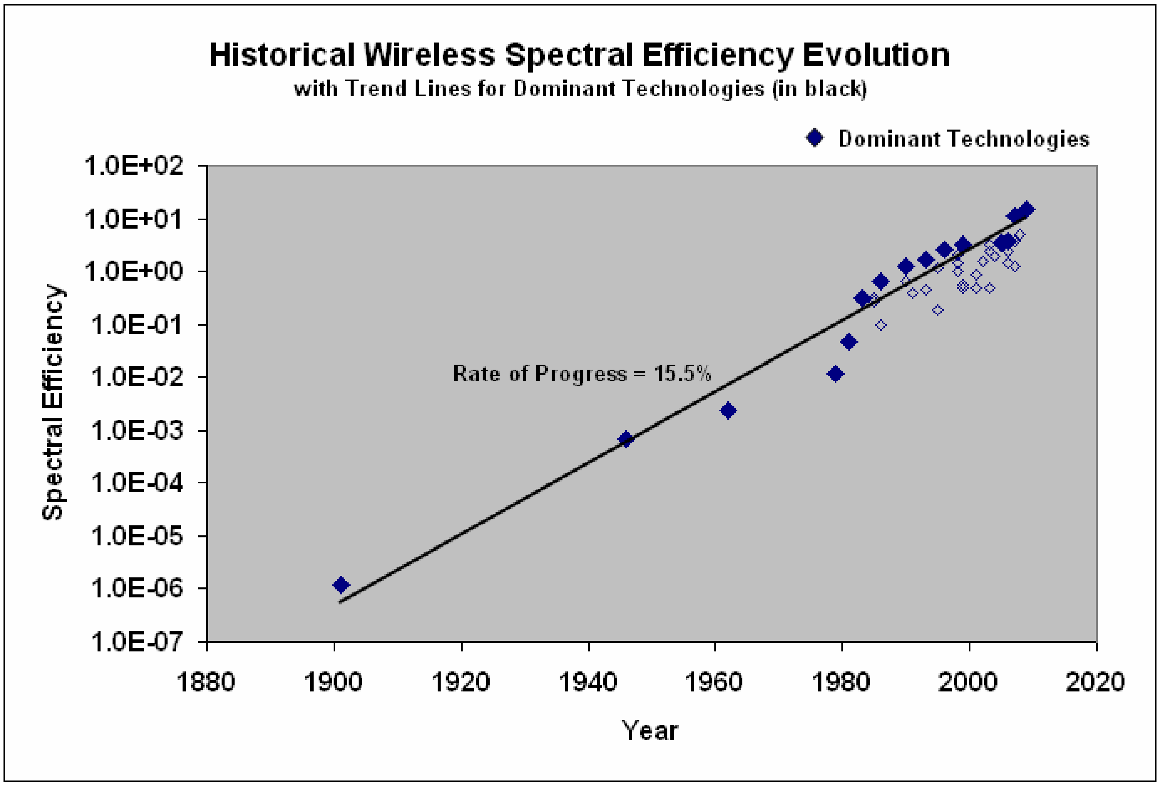

Figure 2: Spectral efficiency FPM

| Regression Analysis: Spectral Efficiency | | | | |
|---|---|---|---|---|
| | Regression Equation | Progress Rate | Goodness-of-fit (R Square) | Significance Test (F-Test) Probability |
| Dominant Technologies | y=5E-07*exp(0.1542*x) | 15.5% | 0.96 | 1.31E-10 |

Table 4: Regression Results for spectral efficiency dataset

## Coverage Density

The coverage density FPM has sustained high rates of growth over the full 100 plus year period as observed in figure 3. As for spectral efficiency, the progress rate has been consistent over the period (33% in this case) but this is not quite as firm as for spectral efficiency as seen by the lower fit parameters in Table 5. The recent progress is felt to be mainly due to the developments in WAN and WPN technologies; these technologies offer very high throughputs in relatively small coverage areas (less than 100 meters of range). The result is a high concentration of bandwidth. Figure 3 evidences two separate clusters of data since the late 90’s: the cluster of data on top is the one corresponding to Local-

Area Wireless technologies, while the one below it corresponds to the Larger Coverage Area Technologies.

Regression Analysis: Coverage Density FPM

| | Regression Equation | Progress Rate | Goodness-of-fit (R Square) | Significance Test (F-Test) Probability |
|---|---|---|---|---|
| Dominant Technologies (All Range) | y=7E-14*exp(0.3316*x) | 33.2% | 0.90 | 8.39E-05 |

Table 5: Regression Results for the coverage density dataset

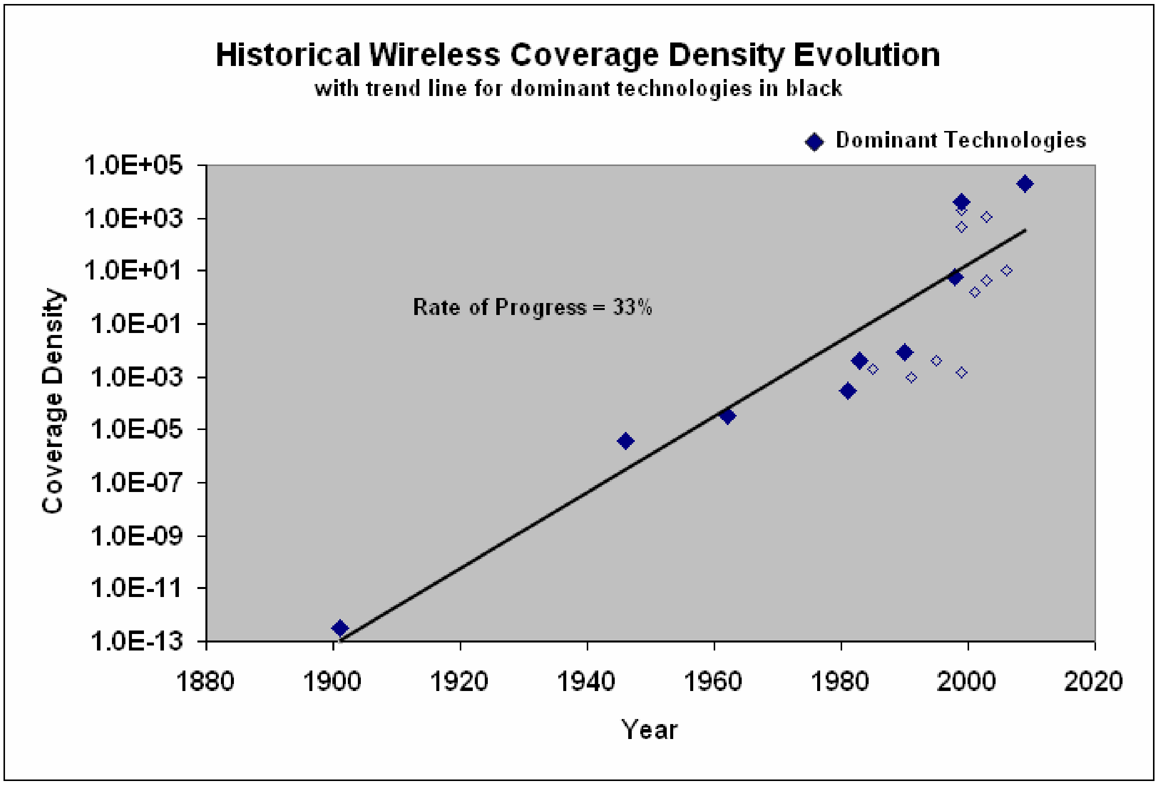

Figure 3: Coverage density for wireless technology

## Discussion

### Analysis of Results

Table IV is a summary of the quantitative fits for the three FPMs. All show that substantial annual progress rates have been achieved. Moreover, this progress is comparable to that found over similar time periods in other information technology FPMs where annual progress rates ranged from 19 to 37% (3). For coverage density and spectral efficiency, there has been *continuous exponential improvement* over the full 100 plus year period (~15% per year for spectral efficiency and ~ 33% per year for coverage density[3]).

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[3] The data is too sparse for coverage density but it may in fact follow several linked exponentials.

| Wireless FPM | Set of Data | Regression Equation | Progress Rate |
|---|---|---|---|
| Throughput | (1895-1979) | y=2.8E-03*exp(0.0516*x) | 5.16% |
|  | (1979-2009) | y=3E-20*exp(0.5124*x) | 51.2% |
| Spectral Efficiency | (1901 – 2009) | y=5E-07*exp(0.1542*x) | 15.5% |
| Coverage Density | (1901 – 2009) | y=7E-14*exp(0.3316*x) | 33.2% |

Table 4: Summary of regressions results for wireless FPMs

Thus, examining these functional engineering tradeoffs over the long term does not reveal the discontinuities due to the numerous breakthroughs in wireless technology. Examination of the technical capability progress at the resolution of 100 plus years renders the stream of technical developments to appear as a continuous phenomenon rather than as a set of discrete changes. Exponential continuity at this resolution has also been observed in FPMs for information storage (3), information transformation (10,3), energy storage(4), and energy transformation (4). Similar to the cellular technology FPMs, numerous technical developments occurred over the 100 plus year period studied in each of these areas. Figure 4 is a schematic representation that has been used to understand the smooth exponential behavior from a set of discrete technical changes (3). The reasons for differing progress rates for different FPMs have only begun to be clearly identified but in this study we note that throughput and coverage density have been affected by hardware, software and system configuration technologies whereas spectral efficiency has largely been driven by increasingly efficient modulation schemes (software only). This may be part of an explanation for the lower rate of improvement for spectral efficiency but demand and industry investment decisions are also likely to be part of an eventual full interpretation.

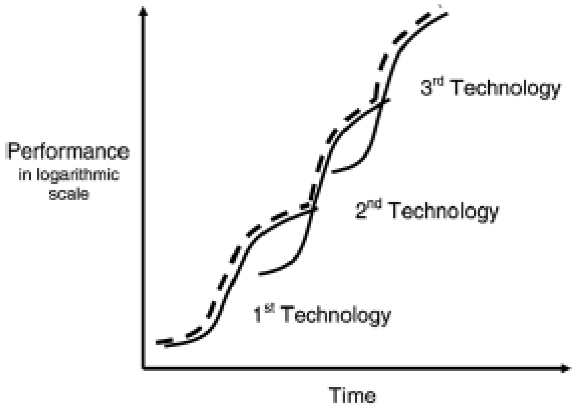

Fig. 4. The “linked S-curve Theory”: growth of technology in form of individual S-curves

In the case of wireless throughput, one major technical change is clearly reflected in the results. This is the cellular concept that was implemented beginning in the late 1970s. At that time, the results show that the rate of throughput progress accelerated from ~5% per year to ~50% per year. A similar discontinuity in slope (but also not in absolute value) occurred in energy transportation late in the 19th century when the newly emerging electrical energy transportation replaced mechanical transportation of energy as the leader in performance (4). In the energy transportation case, the rate of progress increases from ~1.2% (mechanical) to 11% (electrical). In both wireless throughput and energy transport, numerous other technical changes occurred beyond the emergence of cells and electrical energy distribution but none appear strong enough to do more than become part of the continuous exponential progress at a constant rate. In the wireless case, neither discontinuities in level or slope are obvious with successive generations of wireless "standards" since the late 1970s which include important technological transitions such as analogue to digital, etc. Nonetheless, the technical changes associated with these new generations of wireless were the essential causes of the high rate of progress (~50% per year) seen over this period.

## Implications of Results

A more complete view of wireless progress would result from also having FPMs that reflect cost and QOS data which we were not able to access in this study. In addition, the future remains uncertain despite significant regularity over long time periods in the past. Nonetheless, the long term trends in this paper give one some potentially useful input for future planning. Similar to the way that Moore's law has served as a benchmark for planning of future IC developments by SEMATECH and private firms, the results in this paper might aid in wireless future system planning. For example, systems in the 2015 timeframe would be expected to have throughput of $10^{7}$ Kbps and spectrum efficiency of 30bps/Hz. We hesitate to conclude that the coverage density will continue at the same pace as previously because of a possible approaching limit where cell size cannot be usefully reduced below the human scale.

A comparison of the wireless throughput capacity over time with that in wired transmission of information is shown in Figure 5. The data are for the wired throughput from Koh and Magee (3). Each data point is either from the undersea cable or from the Internet backbone as shown in the label in the figure. The lines shown are the fits found in this paper for wireless communication throughput (Table 3). It is clear from Figure 5 that the acceleration of wireless progress at about 1980 (when the cellular concept was first implemented) was necessary for maintaining wireless throughput at a level comparable to throughput by wired information transport. The maintenance of comparability is necessary if new higher throughput applications are to be seen as acceptable through a wireless interface. Thus, the high rate of progress since the implementation of the cellular concept (and the continuous reduction of cell size that followed) was an essential enabler for wireless becoming the interface of choice for the Internet and continued progress at high rates is still probably necessary. Both in the case of the Internet (11) and for wireless technology (5), it has not been possible to foresee the applications and services that emerge. These unforeseen applications have been the economic drivers of the technology development. Nonetheless, many of these exciting and world-changing applications could not have occurred without the fantastic, long term co-evolutionary progress in technical capability documented in this paper.

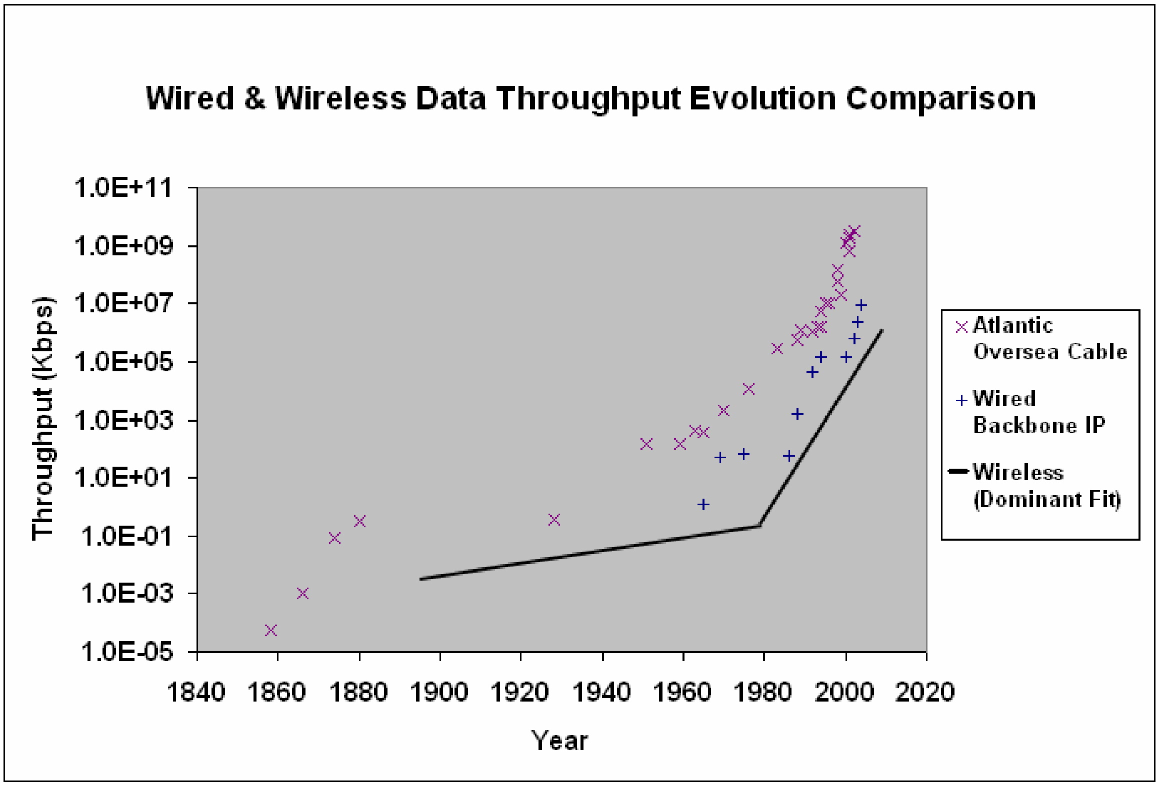

Figure 5: Wireless & Wired throughput

## References

1) H. Linstone, "TFSC 1969-1999", *Technological Forecasting and Social Change* vol. 62, Pages 1-8; this issue of the journal contains a set of linked papers reviewing different approaches to technological dynamics

2) Moore, Gordon E., No Exponential is Forever: But "Forever" can be delayed, IEEE International Solid-State Circuit Conference, 2003

3) H. Koh and C. L. Magee, "A Functional Approach for Studying Technological Progress: Application to Information Technology", *Technological Forecasting and Social Change,* Vol. 73 p1061 (2006)

4.) H. Koh and C. L. Magee, "A Functional Approach to Studying Technological Progress: Extension to Energy Technology" *Technological Forecasting and Social Change,* (2007) doi:10.1016/j.techfore.2007.05.007

5.) Kleinrock, L. "History of the Internet and its Flexible Future" *IEEE Wireless Communications,* Vol. 15, p8, 2008

6) Ohmori, S., Yamao, Y. and Nakajima, N., "The Future Generations of Mobile Communications based upon Broadband Access Capabilities", Vol. 38, p134. This issue contains several other forward-looking assessment of wireless technology

7) Special Issue on IMT-2000: Standards Efforts of the ITU, *IEEE Personal Communications* Vol. 4, pp8-40, 1997

8) Anderson, T.R., Daim, T. U., and Kim, J. "Technology Forecasting for wireless Communication, *Technovation,* (2008),doi:10.1016/j.technovation.2007.12.005

9) Fisher, J. C., and Pry, R. H. "A Simple Substitution Model of Technological Change", *Technological Forecasting and Social Change, p. 75* (1971)

10) Moravec, H. *ROBOT: Mere Machine to Transcendent Mind,* Oxford University Press, (1998)
11) Berners-Lee, T, *Weaving the Web, The Original Design and Ultimate Destiny of the World Wide Web,* Harper Business Press (1999)

## *Appendix on sources and methods*

The performance data about the wireless throughput, spectral efficiency and wireless coverage was collected from several references. Most of the throughput data was found in the Plunkett Research Database. Plenty of additional data was found in various ITU publications or even in individual papers found for each wireless standard. Other remarkable sources of data were textbooks specializing in wireless technologies from several other authors found in the wireless literature. The IEEE Xplore database provided the rest of the data which was found in articles that covered studies of the wireless standards performance in detail. The complete set of data collected with references is included below.

The units defined for the FPMs were not necessarily utilized during the full history of wireless technology. In particular the telegraph and pre-cellular wireless technologies performance was defined in different units, namely "words per minute". These units had to be converted to the FPM units making some reasonable assumptions. For these early technologies (e.g. Wireless Telegraph, MTS and IMTS) some conventions had to be utilized to convert such units into Kbps. As such, it was assumed that to cover any single word, a total of 13 bits would be needed (using 10000 words as a base for that calculation).

Wireless Telecommunications Technology Performance Data Series

| Year | Technology | Throughput[4] (Kbps) | Spectral Efficiency (bps/Hz)[5] |
|---|---|---|---|
| 1895 | Wireless Telegraph | 3.25E-03[1] | |

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[4] For early technologies (e.g. Wireless Telegraph, MTS and IMTS) the throughput of transmission used to be measured in words per minute. As a result, some conventions had to be utilized to convert such units into Kbps. For this, it was assumed that to cover any single word, a total of 13 bits would be needed (using 10000 words as a base for that calculation).

[5] In most cases, the spectral efficiency figure was not directly reported in the references. In such cases, the figure was derived by dividing the reported data rate (throughput) by the reported spectral bandwidth utilized for attaining such data rate.

[6] For the purpose of calculations, the area of coverage was assumed to be approximately circular. The radio of coverage was then used to arrive at the coverage area. The density was thus calculated based on the spectral efficiency of each technology and the 10MHz bandwidth assumption, using the formula coverage density = spectral efficiency * 10 MHz / (∏*range^2)

| | | | |
|---|---|---|---|
| 1901 | Wireless Telegraph - First transatlantic experiment | 1.00E-03[ii] | 1.18E-06[7] |
| 1946 | MTS (Mobile Telephone Service) | 3.51E-02[9] | 7.02E-04[iii] |
| 1962 | IMTS (Improved Mobile Telep Srv) | 7.02E-02[12] | 2.34E-03[13] |
| 1979 | NTT | 0.30[v] | 1.20E-02[15] |
| 1981 | Nordisk MobilTelefoni (NMT-450) | 1.20[15] | 4.80E-02[15] |
| 1983 | Advanced Mobile Phone System (AMPS) | 9.60[vii] | 0.32[viii] |
| 1985 | C-450 | 5.28[15] | 0.26[15] |
| 1985 | TACS | 8.00[15] | 0.32[15] |
| 1986 | Nordisk MobilTelefoni (NMT-900) | 1.20[15] | 0.10[15] |
| 1986 | Mobitex / BSWD | 8.00[xi] | 0.64[21] |
| 1990 | Cellular Digital Packet Data (CDPD), AMPS standard | 19.20[xii] | 0.64[22] |
| 1990 | IS-54 (aka Digital AMPS, D-AMPS, NA-TDMA) | 13.00[17] | 1.30[xiii] |
| 1991 | Global System for Mobile Communications (GSM) | 9.60[17] | 0.38[xiv] |

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[i] J. J. Fahie, A History of Wireless Telegraphy, 2nd edition revised, 1901 (pg. 176-261). Consulted online on March 15 2007 at http://earlyradiohistory.us/1901fa23.htm. A throughput of 15 words per minute was used for this study.

[ii] John S. Belrose, Fessenden and Marconi: Their Differing Technologies and Transatlantic Experiments During the First Decade of this Century, International Conference on 100 Years of Radio, 5-7 September 1995. Consulted online on March 15, 2007 at http://www.ieee.ca/millennium/radio/radio_differences.html. Reports of the letter "S" being continuously transmitted are assumed to represent a rate of transmission of 1 bit / sec for the purpose of this study.

[iii] Richard N. Lane, Spectral and Economic Efficiencies of Land Mobile Radio Systems, IEEE Transactions on Vehicular Technology, Vol. VT-22, No.4, November 1973 (Table 3, Pg. 98). The reported 20 private users in 1MHz figure was utilized for this calculation. For IMTS, a 30 KHz channel bandwidth is used, as reported by Paul Bedell, in his textbook "Cellular/PCS Management: A Real World Perspective", McGraw-Hill, 1999 (Chapter 1, section 1.2).

[iv] R.L. Lagace and H.L. Paatan, PUBLIC MOBILE TELEPHONE: A comparative analysis of systems worldwide, Arthur D. Little Inc. Cambridge, MA (pg.22). A coverage range of 22.5km was used for MTS and 15Km for IMTS for these calculations.

[v] Harald Gruber, The economics of mobile telecommunications Cambridge University Press, 2005 (Table 2.2).

[vi] Sources: Althos publishing at http://www.althos.com/IPTVArticles/iptvmagazine_2007_02_Mobile.htm and Cellular online at http://www.cellular.co.za/celltech.htm (websites consulted online April 4, 2008). Cell Range for NMT reported in the 25 – 40 Km range. Range of 30KM was used (this is the figure reported in Wikipedia).

[vii] Source: Plunkett Research, Mobile Wireless Standards and Throughputs, 2007.

[viii] Harald Gruber, The economics of mobile telecommunications, Cambridge University Press, 2005 (Table 2.2). The actual throughput (equal to 9.6Kbps as reported by Plunkett Research and other sources consulted) is slightly lower than the channel bit rate reported by this source (10Kbps). As a result, the Spectral efficiency calculated is 0.32, instead of the reported 0.33.

[ix] FRANKLIN H. BLECHER, Advanced Mobile Phone Service, IEEE Transactions on vehicular technology, vol. VT-29, no.2, May 1980 (pg. 243). Reported Maximum 10 miles (16Km) was used for the calculations. CDPD cell size is the same as AMPS.

[x] Source: ETSI. Maximum cell radius reported 20Km. Wikipedia reports a range of 15 – 20 Km. 20 Km was used for this study.

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[7] The John S. Belrose reference agrees that the bandwidth used during Marconi's first transatlantic experiment had to be around 850KHz. This figure was therefore used for this calculation.

[8] A distance of 3500Km was used to arrive at this figure.

[9] Since MTS was a one-way, half-duplex communication system, a throughput of 2.7 words per second, corresponding to the normal pace of speaking of an average person, was assumed for this calculation. Similarly, since IMTS was a two-way, full-duplex system, a throughput of twice the one for MTS is assumed, e.g. 5.4 words per second, for the purpose of this study.

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[x] Mobeen Khan and John Kilpatrick, Mobitex and Mobile Data Standards, IEEE Communications Magazine, March 1995 (pg 2). A 12.5 KHz bandwidth was utilized to calculate the spectral efficiency.

[xi] Mobeen Khan and John Kilpatrick, Mobitex and Mobile Data Standards, IEEE Communications Magazine, March 1995 (pg 2). A 12.5 KHz bandwidth was utilized to calculate spectral efficiency.

[xii] Debabrata Saha, Stanley E. Kay, Cellular Digital Packet Data Network, IEEE Transactions on vehicular technology, vol. 46, no. 3, August 1997 (pg. 698). A 30 KHz bandwidth was used to calculate spectral efficiency.

[xiii] J. Webster, Mobile Telecommunications Standards, Wiley Encyclopedia of Electrical and Electronics Engineering, John Wiley & Sons, Inc., 1999 (pg. 388). The bandwidth reported equals 30 KHz for 3 traffic channels. A 10 KHz bandwidth was thus utilized for this calculation.

[xiv] Harald Gruber, The economics of mobile telecommunications, Cambridge University (Table 2.3). The reported 200 KHz for GSM correspond to 8 traffic Channels. Thus, a bandwidth of 25 KHz was utilized for this calculation.

[xv] Jochen H. Schiller, Mobile communications, Addison-Wesley, 2003 (pg. 102). A 35 Km cell range was utilized for this calculation.