A Functional Approach for Studying Technological Progress: Extension to Wireless Telecommunications Technology

By Mario A. Amaya

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Signature of Author ______________________________

Mario Amaya
System Design and Management Program

Certified by ______________________________

Christopher Magee - Thesis Supervisor
Director, Center for Innovation and Product Development, MIT

Certified by ______________________________

Patrick Hale
Director, System Design & Management Program

Abstract

This thesis attempts to study the technological progress of wireless technology and the wireless industry throughout history, using high-level, non-device specific performance metrics. Such metrics are developed by following the broad functional category approach. The analysis performed is both qualitative and quantitative. Firstly, the quantitative study provides a general perspective of how the technology has evolved through history, looking for signs of constant evolution and/or signs of technological saturation or acceleration. Following this, the qualitative section aims to provide the basis of a strategic framework that could be of importance to organizations in the industry, in particular to those interested in making the right decisions regarding technology selection, new spectrum licensing, and new services pricing, by using a cost-benefit approach. It was found that, in concordance with the two previous analyses performed on the information and energy technology domains, a continuous progress in the metrics identified is observed in the three Functional Performance Metrics (FPM) determined for this study. Still, some weak signs of eventual saturation were observed in one of the metrics identified in the study for the first time in this kind of study. A rate of yearly progress of 15% was obtained from the spectral efficiency Functional Performance Metric (FPM), while significantly higher rates, close to 50%, were obtained for both the throughput and coverage density FPMs. The time series comprises over 100 years of data, from the late 1800's / early 1900's until the present.

Introduction

There have been two previous attempts to describe and analyze technological progress through the usage of broadly conceived Functional Performance Metrics (FPM). Koh and Magee provided a relevant study on information technology[1]. They then extended their study to energy technology in a second paper[2]. In the first paper, they set an initial precedent on the FPM methodology, by developing and assessing a broad functional category approach to arriving at metrics for studying technological progress. In applying the approach to three different functional categories, namely, transportation, storage and transformation of information, they observe continuous exponential progress in the technological evolution independent of the specific devices dominating the technological domain throughout the years. As a result, they conclude that the functional approach provides a more stable and reliable methodology for assessing longer time technological trends, at the cost of losing some of the ability to forecast specific dominant technological trajectories. In the second paper, they extend the broad functional category approach developed in the first paper to the energy technology domain. After applying the approach to the same three functional categories, they observe the same degree of reliability, stability and continuity over the technological progression trends through time. They also observe little signs of saturation and the same exponential progression rate that were observed for the information technology case. However, they find some important differences in energy technology, which are: a significantly lower rate of progression, higher progression rate variability among functional categories and a more challenging data recovery and metric definition.

In the present document we are extending the study performed on information and energy technology to the wireless domain. We are basically extending the study of information transportation as the previous work essentially focused upon the undersea cable and other wired approaches in this functional category. In this way, we attempt to both compare the results obtained in this paper with the ones previously obtained and also discuss the basis of a framework that may support wireless industry organizations' strategic decision-making in the areas of technology selection and new spectrum licensing, through the study of historical technological progress of wireless technology, using high-level, non-device specific performance metrics. This thesis thus is the initial study of functional technological progress that explores the business implications of such work.

Functional Performance Metrics

Following the functional technological classification system developed by Magee and de Weck[3], which is defined in terms of operands (Matter, Energy and Information) being changed by operations (Transformation, Transportation, Storage, Exchange and Control), it was found that, due to the nature of wireless technology, the storage and transformation categories have little or no relevance to this technological domain. It was therefore decided to focus the present study in the "Transportation of Information" category, since it is the primary function delivered by wireless. In this functional category, we decided to evaluate 3 aspects of wireless transportation that are among the most important performance characteristics for this category. The functional performance metrics (as previously) are derived from specific important tradeoffs important in the domain. The three FPMs are summarized in the following table:

Operation	Functional Performance Metric	Unit
Transportation	Throughput	Kbps
	Spectral Efficiency	bps / Hz
	Coverage Density[a]	bps / Sqmts

Table 1: Wireless FPMs

We now proceed to elaborate on the importance that these three aspects of wireless information transportation have for the analysis performed in the present paper. The basic function being studied is transport of information. The FPMs of importance consider the performance relative to some key resource and thus explore engineering tradeoffs over time (ref 1 and 2). In this sense, in the first instance, throughput is of critical relevance for assessing wireless technological progress as time is always a relevant resource. Moreover, the air interface has been generally regarded as a very hostile mean for wireless data transmission. In this way, the possibility of accomplishing high rates of progress in throughput despite the hostility of the transmission environment would provide strong evidence of the capacity of technology to overcome these adverse environmental conditions, made possible through the usage of science in the development of increasingly advanced technologies. This would also represent a clear sign of the new business opportunities that may emerge resulting from such technological progress. Secondly, the transportation efficiency in wireless provides an excellent perspective on the ability of the technology to make better usage of the limited resources 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 technological ability to transport increasingly larger amounts of information over this limited resource. For the remainder of the present paper, this aspect will be called spectral efficiency, which is the name most commonly utilized in the industry. And thirdly, using a measurement of coverage provides an appropriate indication of the ability of the technology to transport large amounts of information to an increasingly higher number of people living in increasingly distributed areas.

[a] A normalized spectrum bandwidth of 10MHz was used for required calculations of this FPM.

Case study: Wireless Technology

Characteristics of historical data

A database was created with the 3 Functional Performance Metrics defined for this study. A full set of data was collected from several sources from 1895 to 2007. Among the most important sources we have the IEEE Xplore paper database and information obtained from publications from the International Communications 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 the endnotes of Appendix 1 for a detailed explanation on where and how the numbers for the database were finally obtained and how the calculations were performed whenever needed.

Since the performance of technological progress is measured with the FPM's 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 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 word per minute and therefore a conversion formula was established to convert the data found to the right units of the FPM's (See endnote 17 of Appendix 1 for an explanation of this formula). Beyond this last issue, we can conclude that the error margin is very low for most of the data collected.

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, throughput of mobile station, 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[b] 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.

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 in Appendix 1.

The units defined for the FPMs were not necessarily utilized full history of wireless technology. In particular the telegraph and pre-cellular wireless technologies performance was defined in special units, namely "words per minute" and "cycles per second", these units had to be converted to the FPM units making some reasonable assumptions (see the footnotes in Appendix # 1 for a complete description of the calculations performed).

Brief history of wireless communications

The first proven wireless transmission of data dates from 1896. Guglielmo Marconi was able to transmit radio signals through the air. The initial Operational reports of the wireless telegraph state that signals where transmitted over the air for a distance of 1.75 miles in the United Kingdom. By 1897, the connection distance had been improved to 8 miles. The first transatlantic transmission took place in 1901[4]. A yacht competition was the scenario of the first wireless telegraph demonstration in the US, which, despite being unsuccessful, got the attention of

[b] This is consistent with the two papers of Koh and Magee

American Society. Proof of this was the installation of the first wireless telegraph station in Cape Cod in 1900. By 1912, a network of dozens of stations covered all continents[5]. The first wireless broadcast service started in 1920, while the first television broadcast took place in 1928[6]. The first service available for use by the public, called MTS was started in 1946, with very limited capacity. The system was improved in 1962 with more channels available. The lack of capacity in this initial wireless systems lead to the development of the cellular concept. The first analogue cellular Network was put in operation in 1979 (NMT)[7], while fully digital systems where developed in the early 1990's[8]. Packet data transmission was developed in the mid-60's[9] but became operational only by the late 1990's with the introduction of the Hyper-LAN and Wi-Fi standard families.

Wireless Throughput

The evolution of throughput for wireless technology can be observed in Figure 1. A logarithmic scale was utilized in the graph to enable the observation of the progress made by the technology even during the years when the progress was relatively slow. It is evident in Figure 1 (in contrast to the spectral efficiency FPM) that the rate of progress has not been constant. During the first half of the 20th century, the yearly rate of progress was rather slow. The fact that, during those years, technological development was focused on making wireless voice transmission possible, without much regard to system capacity, explains the slow progress observed during this period. After that, some historical developments in wireless technology significantly boosted the progress of throughput. In contrast to these, 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, clearly boosted throughput performance even further. These two facts together with the development of new technologies that enabled the simultaneous utilization of more bandwidth (e.g. increasing spectral efficiency rates) constitute the main reasons for the significant acceleration of throughput during the 90's.

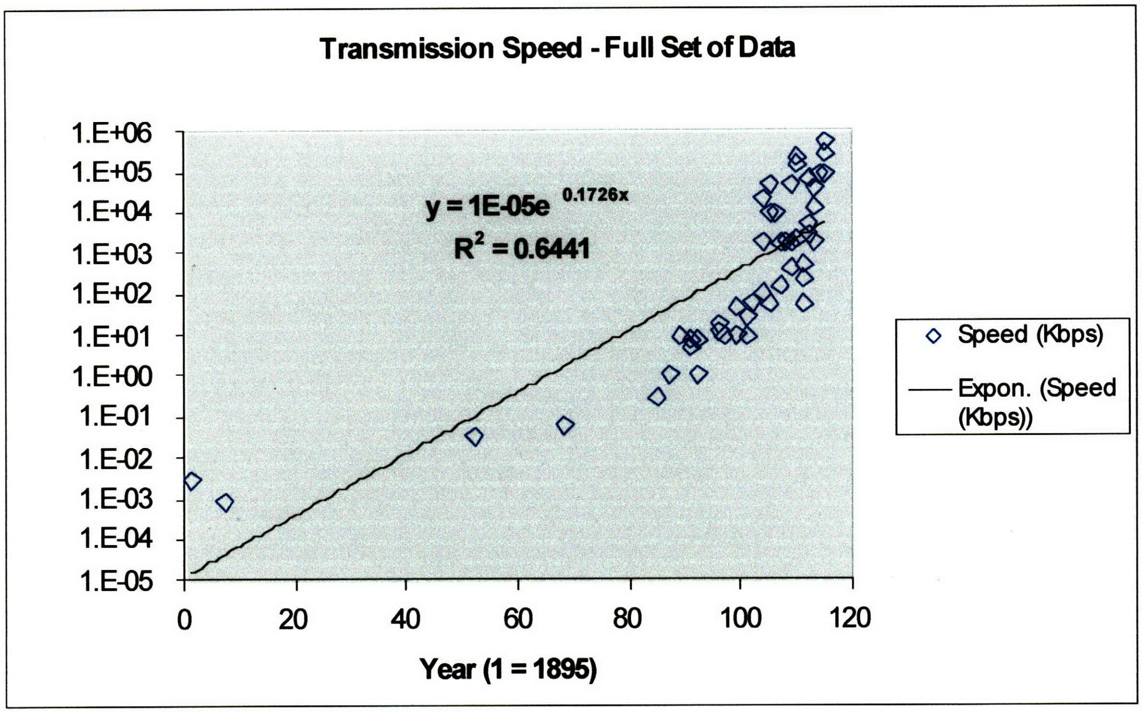

Figure 1: Wireless throughput FPM – Full Set of Data

The poor goodness-of-fit results obtained from the exponential regression performed over the full set of data are evident in Figure 1. After running a preliminary analysis with the complete set of data corresponding to the dominant technologies and observing only marginal improvements in the fits (Figure 2a), the data were divided in two ranges: 1895 to 1979 and 1979 to 2009, and regressions were now conducted for the two sets. The fits of the regressions improved significantly, showing both very good regression fits and statistical significance, as it can be seen in Figures 4b and 4c. 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 year of change of the progress rate coincide with the appearance of the cellular concept indicating the importance of this idea to the progress of wireless technology. Table 2 summarizes the results of all the regressions conducted (The model used was again y=b*exp(c*x)).

Regression Analysis: Throughput FPM

	Regression Equation	Progress Rate	Goodness-of-fit (R Square)	Significance Test (F-Test) Probability
Full Set of Data	y=1E-05*exp(0.1726*x)	17.26%	0.64	2.42E-12
Dominant Technologies (All Range)	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 = 5E-20*exp(0.5078*x)	50.78%	0.91	6.64E-06

Table 2: Regression Results for throughput dataset

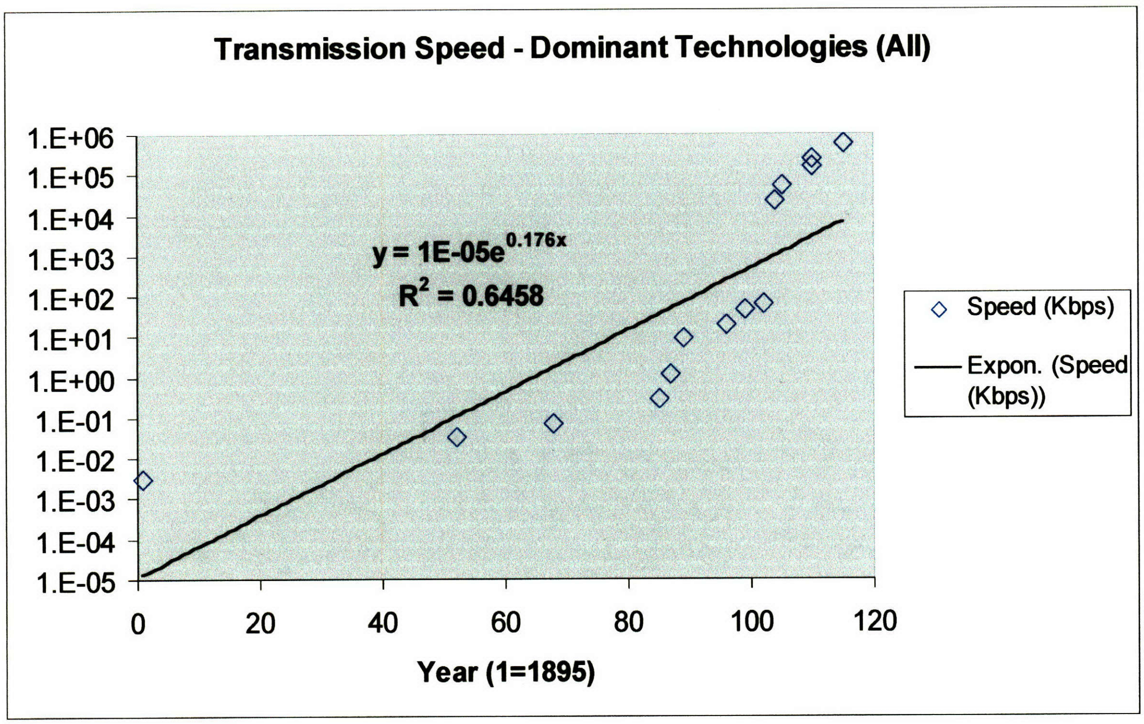

Figure 2a: Throughput progress – Dominant Technologies (Full Range of Years)

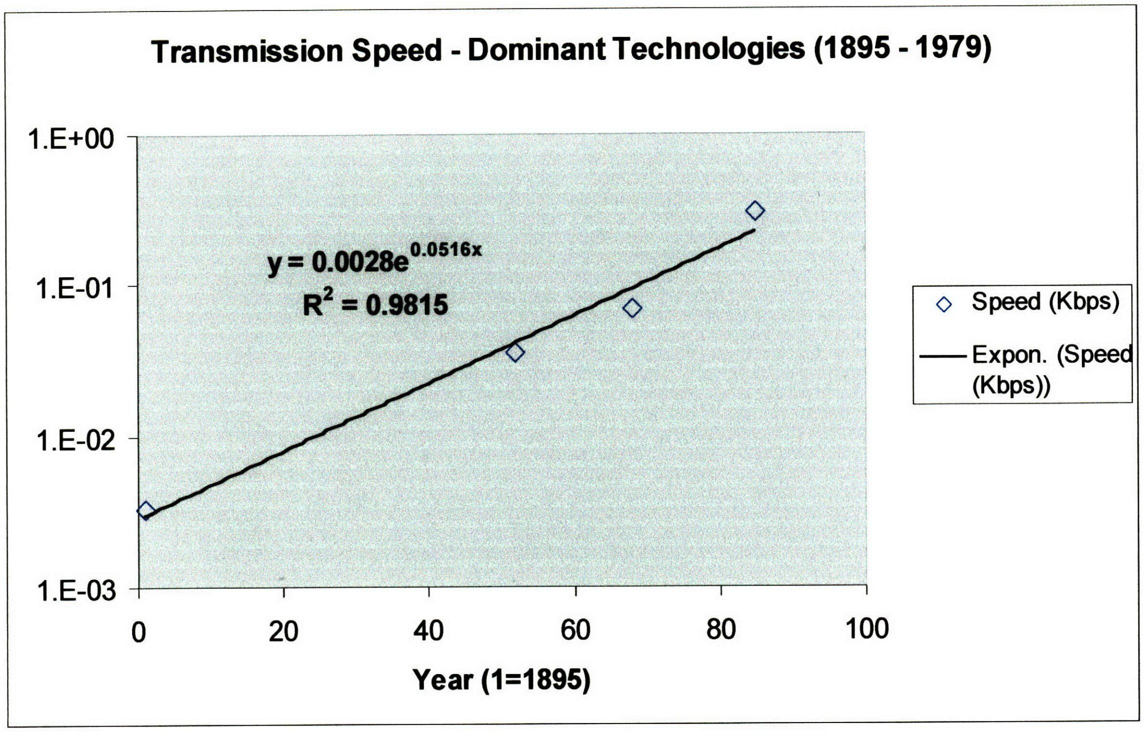

Figure 2b: Throughput progress – Dominant Technologies – 1895 – 1979

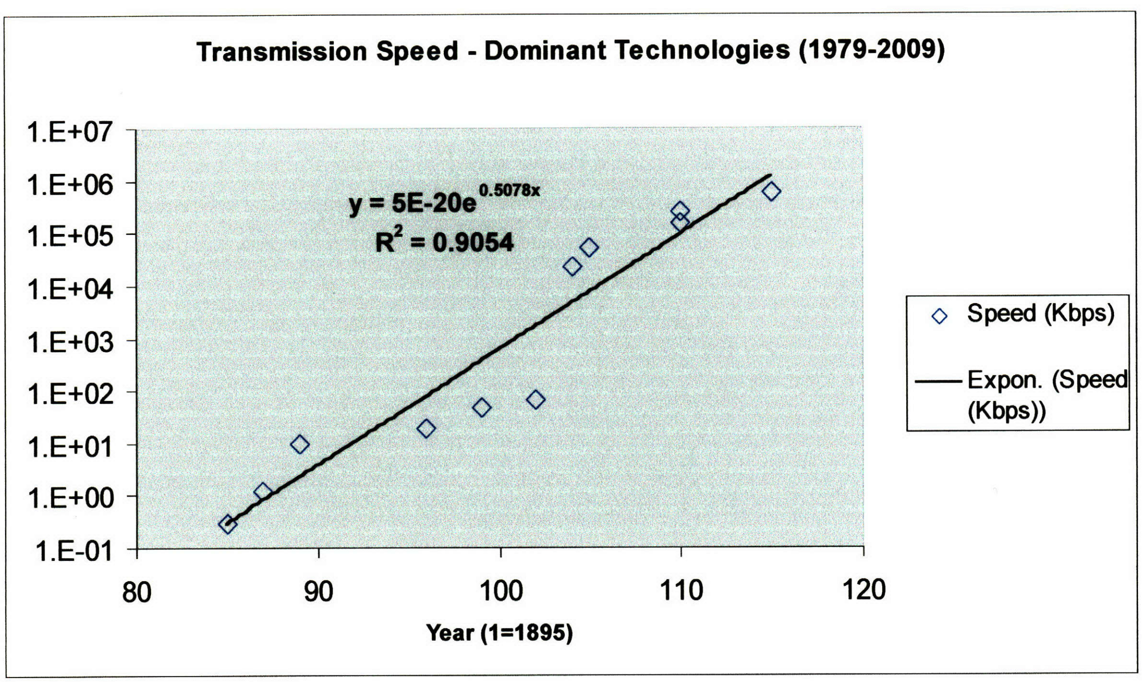

Figure 2c: Throughput progress – Dominant Technologies – 1979 – 2009

The results again provide no indication that wireless technology speed is reaching limits in the set of data collected. On the contrary, the data are consistent with the assumption that the FPM will continue its growth for the years to come. There is more uncertainty on whether the pace of growth will continue increasing. It is usually said that the technology cannot grow forever, but according to the trends it is unlikely to see saturation happening in the next few years. What we can be certain of is that there are no signs of deceleration in the trend until now.

Wireless Spectral Efficiency

Despite the clear interrelationship between throughput and spectral efficiency, the latter is a normalized FPM due to the inclusion of bandwidth in the calculation. By dividing throughput over the bandwidth available, the metric captures the ability of transmitting data over a limited resource. In other words, while the overall throughput may have increased only at the cost of utilizing additional spectrum to reach the high levels of transmission, the spectral efficiency FPM could have only increased by a more efficient use of the spectrum.

Figure 3 exhibits the progress in spectral efficiency over the entire period. The data exhibits a steady, almost constant, rate of progress throughout the full period of analysis. The development of increasingly efficient modulation schemes is the main driver of such pace of growth of spectral efficiency, as observed in Figure 3. Regression analysis confirms this observation, giving 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 14.42%.

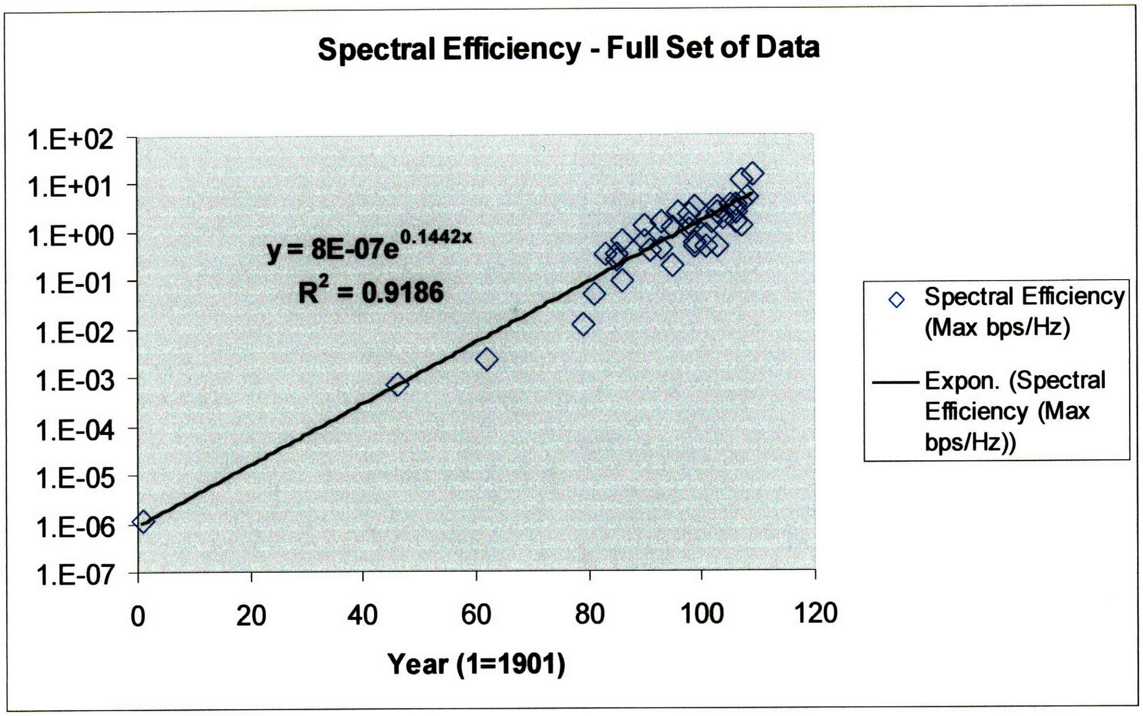

Figure 3: Spectral efficiency FPM (Full Set of Data)

The exponential regression attains an improved fit of the spectral efficiency time series, whenever only dominant technologies are included. A 15.54% growth rate is now attained. An R^2 of 0.96 is reached for dominant technologies, as observed in Figure 4 below.

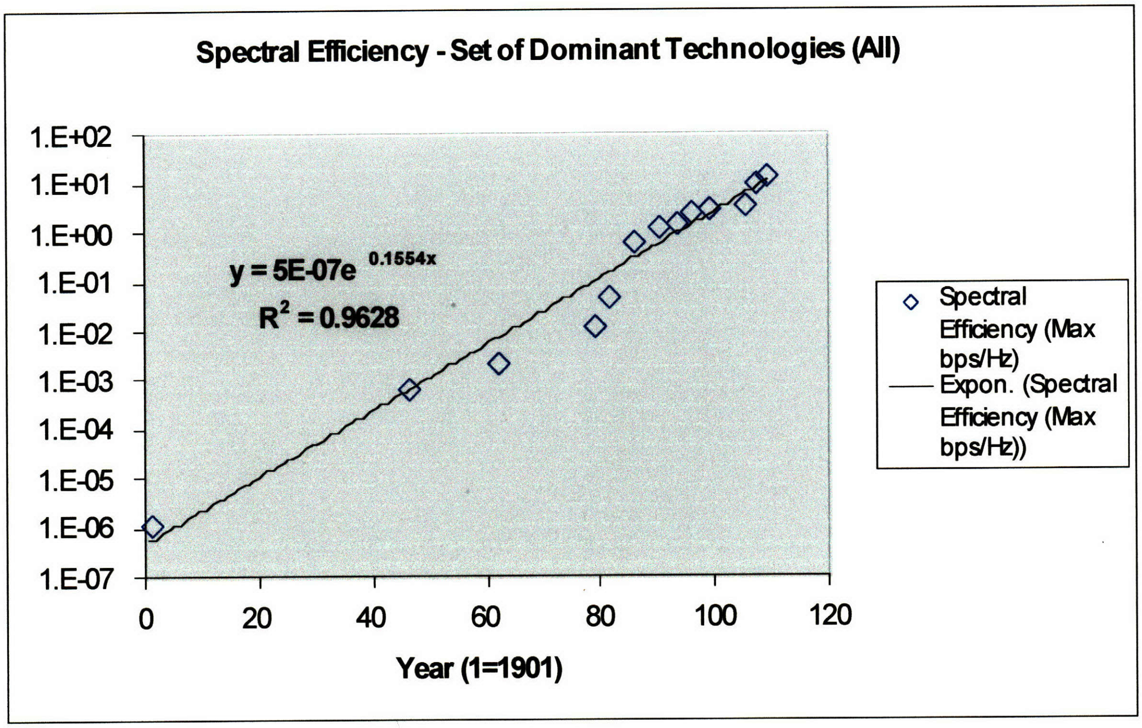

Figure 4: Spectral efficiency FPM for dominant technologies

The results of the regressions conducted on this FPM are summarized in Table 3 below.

Regression Analysis: Spectral Efficiency				
	Regression Equation	Progress Rate	Goodness-of-fit (R Square)	Significance Test (F-Test) Probability
Full Set of Data	y = 8E-07*exp(0.1442*x)	14.42%	0.92	6.01E-24
Dominant Technologies	y = 5E-07*exp(0.1554*x)	15.54%	0.96	3.27E-09

Table 3: Regression Results for spectral efficiency dataset

No signs of progress deceleration were found in the data collected. As a result, it seems unlikely that the technology will reach its physical limits within the next years. This assertion is reinforced if it's taken into account that higher levels of throughput have been attained by finding new ways of encoding the data (without the need of additional bandwidth). This technological development is independent of the physical limitations of the radio spectrum.

Coverage Density

Progress in wireless coverage has been determined by both the development of the cellular concept and the improvements in spectral efficiency. It is important to notice that in wireless technology, there is a strong relationship between the coverage and the throughput offered by a source: the larger the coverage, the more likelihood of signal loss (fading), which implies lower throughputs. This relationship is mathematically established by the following formula:

$$\begin{aligned} \text{FSPL} &= \left(\frac{4\pi d}{\lambda}\right)^2 \\ &= \left(\frac{4\pi d f}{c}\right)^2 \end{aligned}$$

Exhibit 1: Free space Path Loss (FSPL) Formula

Where:

- FSPL is the Free Space Path Loss
- λ is the signal wavelength (in meters)
- f is the signal frequency (in Hertz)
- d is the distance from the transmitter (in meters)
- c is the speed of light in a vacuum, 2.99792458×10^8 meters per second.

The size of a wireless area of coverage is therefore determined by the frequency. In more simple words, the higher the frequency, the smaller the area of coverage.

The coverage density FPM has sustained high rates of growth in recent years, as observed in figure 5. This fact is explained mainly by the important developments performed 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 5 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. This fact results in a relatively weak goodness-of fit. The rate of progress for the full set of data equals 32%. We then proceeded to perform an exponential regression (model y=b*exp(c*x)) using the set of dominant technologies, and once again the regression fits improved significantly. The yearly rate of progress for the coverage density FPM reaches 33% in this case. Results of the regressions are summarized in Table 4.

Regression Analysis: Coverage Density FPM

	Regression Equation	Progress Rate	Goodness-of-fit (R Square)	Significance Test (F-Test) Probability
Full Set of Data	y=7E-14*exp(0.3183*x)	31.83%	0.78	4.52E-07
Dominant Technologies (All Range)	y=7E-14*exp(0.3316*x)	33.16%	0.90	8.39E-05

Table 4: Regression Results for the coverage density dataset

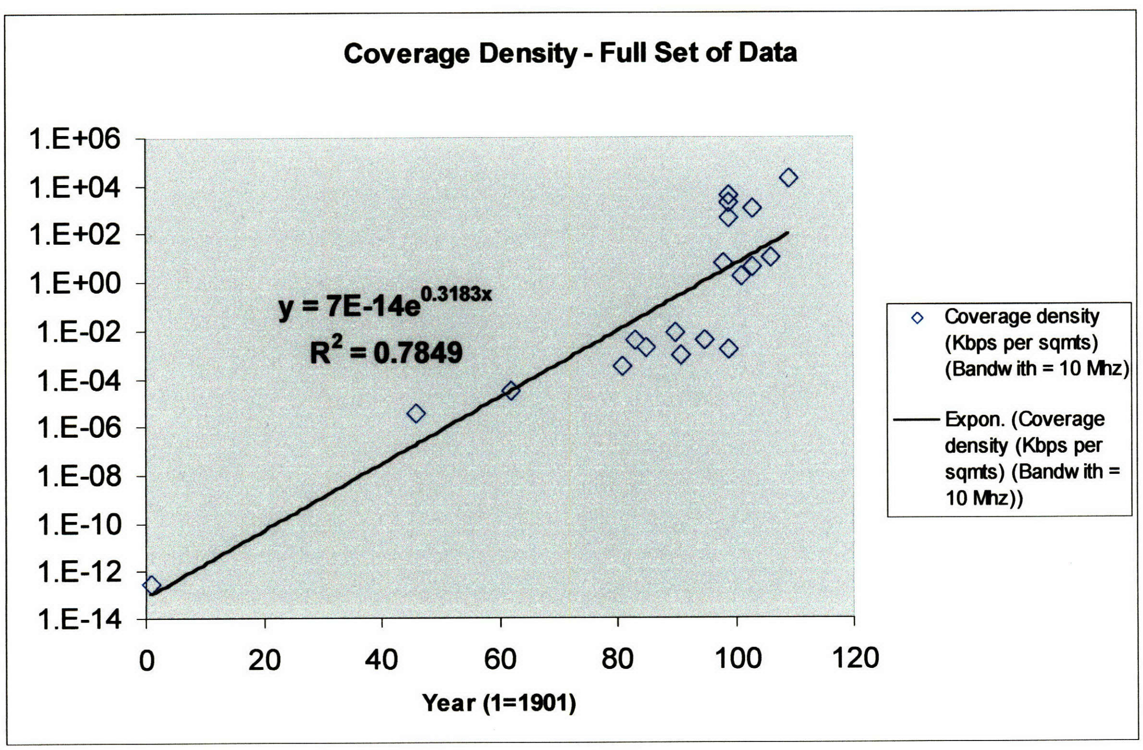

Figure 5: Coverage density for wireless technology

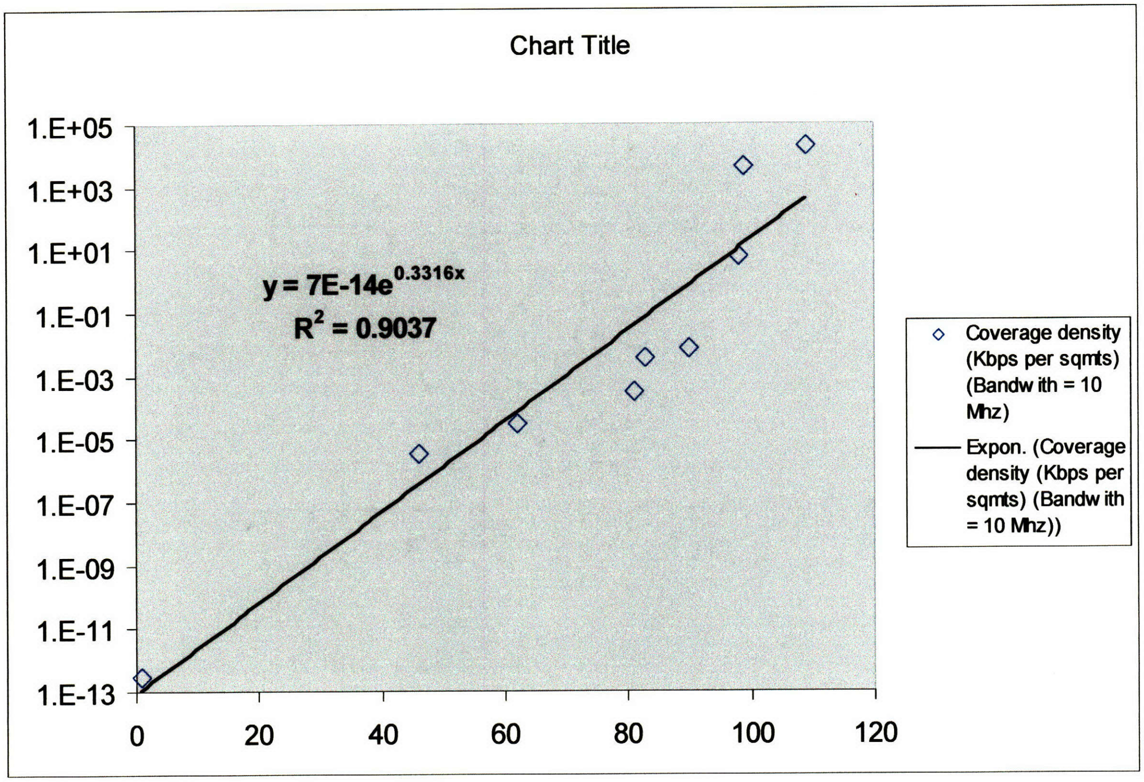

Figure 6: Coverage density for dominant technologies

In contrast with the two FPM's previously discussed, some signs of possible deceleration in the pace of growth are observed in the latest years. While this effect is of much too short a duration to be statistically certain, it should be noted that a physical limitation which does not affect the other two FPM's is apparent in the coverage density FPM: the size of the cells. Wireless cells can hardly become smaller than what they are now for WAN or PAN technologies (802.11 has a typical reach of 30 meters) to remain operational and functional. The small size of the cells in these short-range technologies has been an important determinant in the progression of its throughputs. Moreover, many of the new generation modulation schemes utilized in these technologies are among the most efficient in the industry, meaning that significant improvements in this regard will be more difficult to obtain for short range technologies compared to long-range technologies. Cells will hardly become smaller as its size is reaching the minimum values relevant for the human scale. As a result, we can anticipate that the rate of improvement in coverage density may tend to decelerate in the near future.

Analysis of Time Dependence of Functional Performance Metrics

After reviewing the behavior of the three FPMs and their rates of growth, we discuss variation among the way the rates of progress in these three metrics were impacted by the major events in the development of wireless. Most importantly, while the introduction of the cellular concept in the late 70's produced a sustained boost in the rate of growth of the Transmission Speed FPM, this was not the case for the Spectral Efficiency and Coverage Density FPMs. Understanding the three major elements of growth in wireless performance could shed light on the reason behind such behavior:

a. Size of Cell: in general, making the size of cell smaller enables the sustained transmission of data rates, due to more favorable path loss conditions, as explained by exhibit 1.
b. Usage of more simultaneous spectrum bandwidth: in general, the simultaneous utilization of more bandwidth increases overall system capacity, enabling faster data rates.
c. Introduction of new generation modulation schemes: it is still possible to increase the capacity of wireless systems without the usage of more physical bandwidth, through the incorporation of high efficient modulation schemes, which enable the transportation of more sets of data (bits) using the same spectrum resource.

In theory, we can see that while all three factors can impact the growth of the throughput FPM, only two of them (size of cell & new modulation schemes) can do it for the spectral efficiency and coverage density FPMs. We can observe in the plots of the three FPM's that some boost was introduced in their rates of growth after the introduction of the cellular concept. However, only the wireless throughput was able to sustain its growth over the years. This situation was observed also in the late 90's with the introduction of the WLAN technology (that brought the size of the cells down to have it in the order of scale of the size of a human being), which initially boosted the coverage density FPM, without being able to sustain the rapid progress (since the size of the cells could not be made much smaller).

The cellular concept enabled the reutilization of frequencies within different cells at a certain distance, which dramatically increased the capacity that wireless systems could attain. It was only then that wireless technology attracted the attention of business, due to the possibility of reaching virtually any consumer was finally a reality. Posterior large investments in technological development enabled the generation of the new technologies that enabled the observed fast progress of wireless performance. Without any doubt, the introduction of cellular is the most significant event during the wireless era.

Comparison with wired information transportation rates of progress

In the prior study of Information Technology, Koh and Magee found yearly rates of progress in throughput (which they refer to as bandwidth[c]) of 18.9% and 34.7% for the entire set of data and the 1940 – present data series, respectively. Given these figures, we can observe that while the rate of progress for the entire period of study is similar to the rate obtained in this study for the whole period (17.26%), the rate of progress for the most recent period (1979-present) is considerably higher for the case of wireless (50.78%). Moreover, the change in the rate of progress in the two separate periods is much more accentuated for the wireless case. This finding can be explained by the significant constraint that a limited radio spectrum resource imposed on the evolution of wireless, constraint that was not present in the wired case. Only until this physical limitation was overcome (with the introduction of the cellular concept in the late 70's) the rate of wireless could experience much faster progress.

Wireless Business Discussion

Strategic implications of the trends found in wireless FPM's

It is important to note that it is impossible to predict with any reasonable level of accuracy the long term evolution of any technological progress, and wireless is no exception to this rule. Strategic decision makers should be advised that the trends presented in this paper are required to be updated on a frequent basis, to ensure the appropriate detection of any change in current trends to better inform the decision making process. Despite this uncertainty, the FPM trends

[c] The name bandwidth was not utilized for wireless given the confusion that could be introduced with the physical bandwidth (e.g. spectrum bandwidth), which is in general different from the actual speed of data transmission.

observed in the graphs presented in the previous chapter provide important information that may be used for supporting strategic decision making processes in the wireless industry, specifically for relatively short term decision making (e.g. less than 3 years). More specifically, the information found should support three decision processes: First, investment decision in new technologies as opposed to investing in additional spectrum licensing, second, pricing of wireless services to ensure return over investment before current technology runs obsolete, and third, performance goal setting for wireless equipment developers, for concept selection support.

<u>Investment decision in new technologies as opposed to investing in additional spectrum licensing</u>

The current observed trend in the spectral efficiency FPM provides evidence of fast progression of such performance metric which shows no signs of deceleration, at least in the near future. Analyzing this fast rate of technological progress with current spectrum licensing and equipment costs trends should provide a reliable basis for deciding if any dollar is better invested in new network equipment, new in spectrum licensing, or a combination of both. Current wireless services demand trends should also be considered in this analysis.

Several business scenarios could be obtained in this regard. On one hand, if the current spectral efficiency progress suggests a high likelihood of outweighing the spectrum licensing costs, investment should be concentrated in the acquisition of new technologies that take better advantage of current available spectrum. On the other hand, if the spectrum efficiency FPM shows signs of deceleration, a higher value of spectrum licensing investments would obtain. Due to the presence of uncertainty in future technological trends, decision makers should be advised to consider investments in several different options. Regardless of the trend that presents at a given time, wireless service providers are advised to make small investments in the initially estimated less likely option to keep it valid and have the chance to execute it in case the actual technological conditions happened to be different from the ones that had been regarded as most likely. If, for example, current technological conditions lead to decide to concentrate investments in last generation network infrastructure, small investments in remaining spectrum licensing options open for the near future still need to be considered. Extensive literature in the topic of real options is available nowadays, which provides a quantitative support of such kind of decisions.

Assuming that the rate of growth observed in the spectral efficiency FPM remains constant at least for the next few years, wireless carries can expect to have their system capacities doubled in a bit less than 5 years[d], without requiring any additional spectrum licensing. Using this information together with the costs of licensing and new generation equipment and the wireless services demand forecasts, wireless carriers have a better basis to arrive at the most cost-effective decision, depending on their current system capacity availability. The most cost effective decision could be the replacement of current equipment with new generation one with no need of licensing, the acquisition of new spectrum license (with no equipment replacement) or a combination of both.

Pricing of wireless services to ensure return over investment before current technology runs obsolete

The wireless transmission speed FPM should provide a basis for analyzing the period of time that current wireless technologies take to become obsolete. As discussed in the previous section, the current rate of progress of this FPM is very high. As we had seen in a previous section, the rate of growth during the last 30 years has been 51%. At the current pace of growth, transmission speeds would be tripled in less than three years[e]. As a result, it is expected that increasing pressures on wireless services providers will take place in the next years. Wireless carriers should be advised to include this information as an important factor for pricing decisions. Prices need to be set accordingly, to ensure a return on investment that satisfies the company's shareholders requirements. In this regard, it is important to keep in mind that market performance requirements are usually not uniform throughout a region or even a city. As a result, relocation of current network equipment to different market areas is a clear possibility, and its implementation reduces the financial pressures derived from new equipment and new licensing

[d] The fitted regression function y = 5E-07 * exp (0.1554 * x) was used to calculate this figure.
[e] The fitted regression function y = 5E-20 * exp (0.5078 * x) was used to calculate the figure.

investments. Consequently, strategic rules derived from the trends of progress in transmission speed should not be applied uniformly in all coverage areas.

Given the current trends in transmission speed, it is likely that the technologies available at the moment will become obsolete in less than 3 years for the immediate future, since transmission speed will be more than tripled by then.

<u>Performance goal setting for wireless equipment developers, for concept selection support</u>

With the current trend of more equipment being developed from more equipment suppliers, wireless equipment is tending to become a commodity. It is therefore particularly important that equipment development companies give special attention to performance so that they can differentiate for other providers in the wireless equipment marketplace. The three defined FPMs in this paper should serve as an important reference for wireless equipment development companies. As we have seen, the observed trends indicate that performance goals for new equipment should be set at increasingly high levels, if providers want to extend the lifecycle of their new products, because devices will tend to become obsolete in 3-5 years. Current trends indicate that wireless services providers are in need of high performance equipment that take more advantage of the scarce and very expensive spectrum bandwidth, and also enable them to offer the latest bandwidth hungry applications that its customers are demanding. As a result, performance goals for new equipment should be set at even higher levels than ever before.

Current trends indicate that five years from now, the performance requirements for wireless equipment in terms of spectral efficiency will be in the order of 20 bps / Hz[f].

Conclusions

- Wireless communication has been characterized by three FPMs which are spectral efficiency, transmission speed and coverage density. Over the long term, the first has

[f] The fitted regression function y = 5E-07 * exp (0.1554 * x) was used to calculate the figure.

increased at a yearly rate of 15% during the past 110 years, while the second has done it at a rate of 17% (51% in the past 30 years) and the third one by a rate of 33%. Current trends observed in the FPM's thus indicate a fast rate of progress in wireless technological evolution. While it seems reasonable to expect no changes in the trend observed for both the transmission speed and spectral efficiency FPM, it does not seem to be the case for the wireless density FPM. The fact that the size of cells have been brought down to only a few meters and that modulation schemes are most efficient in short ranges indicates that deceleration is likely and may even be beginning to appear in the coverage density FPM in recent years. Observations of this trend in the next few years will be necessary to determine whether the observed trend in this FPM a real indication of technological limits.

- The three most significant events in the evolution of wireless communications that accelerated progress observed in this technology domain are: the introduction of the cellular concept in the late 70's, the digitalization of the technology in the late 80's (together with more efficient modulation schemes) and the invention of the packet-switching technology (as a replacement of the traditional circuit-switching technology), which came together with the invention of high efficient modulation schemes in the late 90's.

- The information collected in the present research provides valuable input for wireless business strategic decision-making. More specifically, it may be used to support the following business processes:

  - Investment decisions: whether investing in new network infrastructure on in additional spectrum licensing looks more promising in the near future.
  - Pricing: price services accordingly to ensure ROI before current technology runs obsolete.
  - Performance goal setting for wireless equipment developers, to increase its chances of success in the marketplace.

Recommendations for future work on the topic:

- Study additional performance metrics that describe the quality of the wireless connection (Bit Error Rate, Frame Error Rate).
- Correlate the technological performance measurements (FPM's) defined in this paper with the technological costs of acquisition.
- Attempt to explain the observed trends in terms of dominant and not dominant feedback loops, may provide a more accurate technological prediction model. The System Dynamics modeling methodology might support this process very well.

Appendix 1: Wireless Telecommunications Technology Performance Data Series

Year	Technology	Throughput[g] (Kbps)	Spectral Efficiency (bps/Hz)[h]	Coverage Density (bps per Sqmts, Bandwidth = 10 MHz)[i]
1895	Wireless Telegraph	3.25E-03[10]		
1901	Wireless Telegraph - First transatlantic experiment	1.00E-03[11]	1.18E-06[j]	3.06E-13[k]
1946	MTS (Mobile Telephone Service)	3.51E-02[l]	7.02E-04[12]	3.58E-06[13]
1962	IMTS (Improved Mobile Telep Srv)	7.02E-02[12]	2.34E-03[13]	9.93E-06[14]
1979	NTT	0.30[14]	1.20E-02[15]	
1981	Nordisk MobilTelefoni (NMT-450)	1.20[15]	4.80E-02[15]	3.02E-04[15]
1983	Advanced Mobile Phone System (AMPS)	9.60[16]	0.32[17]	3.98E-03[18]
1985	C-450	5.28[15]	0.26[15]	2.10[19]
1985	TACS	8.00[15]	0.32[15]	
1986	Nordisk MobilTelefoni (NMT-900)	1.20[15]	0.10[15]	
1986	Mobitex / BSWD	8.00[20]	0.64[21]	
1990	Cellular Digital Packet Data (CDPD), AMPS standard	19.20[21]	0.64[22]	7.96E-03[19]
1990	IS-54 (aka Digital AMPS, D-AMPS, NA-TDMA)	13.00[17]	1.30[22]	
1991	Global System for Mobile Communications (GSM)	9.60[17]	0.38[23]	9.98E-04[24]
1993	IS-136 (aka D-AMPS, TDMA)	48.60[17]	1.62[24]	
1993	Personal Digital Cellular (JDC/PDC), Japan, TDMA standard	11.20[17]	0.448[24]	

[g] 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).

[h] 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.

[i] 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)

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

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

[l] 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.

1995	IS-95A (aka cdmaOne, CDMA)	9.6[17]	0.19[25]	
1995	TETRA R1 (Terrestial Trunked Radio)	28.80[26]	1.15[27]	4.05E-03[27]
1996	Integrated Digital Enhanced Network (iDEN), TDMA standard	64.00[28]	2.56[29]	
1998	IS-95B CDMA	115.20[30]	2.16[31]	
1998	DECT - Digital Enhanced Cordless Telecommunications	2000[32]	1.04[33]	5.90[33]
1998	HiperLAN1	23,500[33]		
1999	GSM – HSCSD	57.60[34]	0.58[35]	1.50E-03[25]
1999	802.11b (Wi-Fi)	11,000[35]	0.50[36]	2,030.03[36]
1999	802.11a	54,000[37]	3.25[38]	4,141.86[40]
1999	HiperLAN2	54,000[38]	3.25[39]	460.21[40]
2000	HomeRF2	10,000[39]		
2001	GSM General Packet Radio Service (GPRS)	171.20[40]	0.86[41]	1.63[44]
2001	Wideband Code Division Multiple Access (W-CDMA)	1,920[41]	0.5[42]	
2002	CDMA2000 1x Radio Transmission Technology (1xRTT) - Release 1	2,000[55]	1.6[55]	
2003	GSM Enhanced Data Rates for GSM Evolution (EDGE)	473.60[43]	2.37[44]	1.80E-01[44]
2003	Universal Mobile Telecommunications System (UMTS - WCDMA)	1,920[42]	0.5[43]	
2003	802.11g	54,000[44]	3.25[39]	1035.46[45]
2004	HiperLink	155,000[45]		
2004	CDMA2000 EV-DO (Evolution-Data Optimization) Rev. 0	2,400[46]	1.92[47]	
2004	ZigBee	250,000[47]		
2005	PHS (Willicom) - AIR EDGE 8x	256.00[48]		
2005	Wideband Integrated Dispatch Enhanced Network (WiDEN)	60.00[17]		
2005	TETRA R2 (Terrestial Trunked Radio)	538.00[49]	3.59[50]	
2006	CDMA2000 EV-DO Rev. A	3,100[47]	2.48[47]	
2006	CDMA2000 EV-DO Rev. B	73,500[47]	3.68[47]	
2006	Worldwide Interoperability for Microwave Access (WiMax); IEEE 802.16; Mobile WiMax	70,000[50]	3.50[51]	11.14[51]
2006	HSUPA	5,760[52]	1.50[m]	
2007	TD-SCDMA	2,000[53]	1.25[54]	
2007	High-Throughput Packet Access (HSDPA)	14,400[54]	3.50[53]	

[m] Several References (Including Mishra and Philips) report 5MHz as the bandwidth employed for HSPA family (HSUPA, HSDPA) as part of the WCDMA standard). However, Kaaranen et All explain that only 3.84MHz of bandwidth is actually employed. 3.84MHz was used for this study.

2007	HSPA+	42,000[17]	10.94[55]	
2009	802.11n	600,000[56]	15[57]	4,690.19[57]
	High Throughput OFDM Packet Access (HSOPA) – UMTS			
2008	LTE	100,000[58]	5.00[59]	
2009	3GPP Project 2: Ultra Mobile Broadband (UMB)	288,000[59]	14.40[59]	

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