Wireless Communications Devices and Technology: Future Directions

Ken Hansen (ekh002@email.mot.com)
Motorola, Inc.
Land Mobile Products Sector
8000 W. Sunrise Blvd.
Plantation, FL 33322

ABSTRACT

The wireless communication marketplace has enjoyed enormous growth over the last decade. This paper takes a look at what new applications, services, and technology will be required to continue this growth into the future.

1. INTRODUCTION

The successful worldwide deployment of both first generation analog and second generation digital cellular systems like GSM, PHS, and iDEN has changed the wireless communications market's primary focus from professional to consumer. Beside the growth of the equipment manufacturers like Motorola, Nokia, and Ericcson, a new wireless communication device market segment has been created in the semiconductor industry. A similar growth has been seen in the battery industry. In order to differentiate products, and to satisfy the appetite of the consumer in the future, more features and services must be provided. Recently, subscriber units containing multiple services, such as GSM (cellular) and DCS 1800 (PCS), have been introduced. Furthermore, Motorola offers in its iDEN technology, a combination of dispatch, cellular, and paging services. To accommodate and accelerate the growth of subscriber units of ever increasing complexity and capability in the future, cost effective and power efficient multi-band, multi-mode transceivers will be required. In addition, new uses for data, particularly at higher data rates such as required for the transmission of high frame rate video will likely drive many future applications. These new applications place new requirements on technology, and new challenges for technologists.

2. MARKET TRENDS

It has been estimated that by the year 2010 the number of wireless subscribers will reach one billion and exceed the number of wireline subscribers. [1] However, in developed nations, wireless and wireline services will coexist well into the 21st century. The wireline environment is considerably less hostile than the wireless environment and for that reason will provide higher data rates as advances in technology are made (for example, Asynchronous Digital Subscriber Line or ADSL). On the other hand, the untethered nature of a wireless device has the benefit of providing nearly ubiquitous coverage at an albeit reduced service level compared to its wireline counterpart. What will become important is that wireline standards will need to be influenced by wireless technology needs in order to provide a new seamless interface. The overall wireless communication market can be viewed as in Figure 1 [2] where either available or planned services are identified on a plot of mobility versus data rate. The trend for cellular or cellular-like services has been the convergence of different wireless technologies into the same subscriber unit to provide more flexibility to the user. An example of this in the US is the combination of PCS and analog cellular phones operating in different RF bands (1.9 GHz and 800MHz), with different access schemes (CDMA and FDMA), and different modulation schemes (BPSK and FM) while providing enhanced audio quality and talk time in PCS mode and enhanced coverage in analog cellular mode. A similar situation exists in Europe where GSM and DCS 1800 services are being provided in the same subscriber unit . Newer technologies such as Motorola's iDEN technology have built into the air-interface protocol the capability for a cellular-like phone interconnect service, instantaneous and direct connect individual or group call service, a paging service, and a short message service. This technology essentially combines a cellular phone, two way radio, and a pager into a single unit. Other communications developments will focus on 3rd generation cellular and short range communications.

The primary benefit of wireless communications today is to provide voice communications in an untethered fashion that approaches the capability to communicate anytime, anywhere as well as data communications for remote control and paging. There are obvious market trends that can be obtained from learning curves that suggest cost, size, current drain, and weight must continually improve to sustain or grow the market. In order to identify less obvious growth opportunities that may occur, it is necessary to understand where and why a wireless communication device could be used.

There are three places where people spend the majority of their time: 1) home, 2) office or workplace and 3) vehicle. To date,wireless communications have had impact in the office in the form of paging, in homes in the form of cordless telephone, garage door openers, and TV remote controls (infrared), and in the vehicle in the form of cellular phones. These capabilities still represent a rather limited amount of service and therefore leave tremendous opportunity for growth. For the consumer or professional, wireless solutions that save time, money, or effort, provide entertainment/enjoyment, improve health, or improve family relationships will provide a value proposition to capture the untapped market space. The key to being successful is the ability to bring to market the solution at the point where the technology is mature enough to make it cost effective. In a sense, identifying devices of value while ignoring technology limitations is easy. Take, for example, the wristwatch radio first suggested in the Dick Tracy comic strip in the 1930's. As of yet, this concept has not come to fruition although wristwatch pagers have been commercially available since 1991. Additionally, Bell Labs introduced the Picture Phone roughly 25 years ago [3] which provided a video conferencing capability. The concept has been again reintroduced in the 1990's yet neither launch has been successful to date. From these two examples, which will likely be successful in the first decade of the 21st century , it can be seen that it is crucial to align the concept with the technology capabilities and the value to the end user. At the same time, predicting discontinuities in the market place is virtually impossible. Probably the best example of this today is the emergence of the World Wide Web (WWW). For the WWW to be as pervasive as it is today, six key events had to take place: 1) establishment of the infrastructure to form the network, 2) penetration of PC's into the household, 3) inclusion of a modem on virtually every PC, 4) efficient router technology, 5) development and distribution to the masses, at no charge, of a user friendly browser, and 6) useful information created and added to the WWW by the user base. Clearly the WWW has reached such a level of widespread public acceptance that the capability to browse the WWW will be demanded in future generation wireless communications products. A typical file today is on the order of one megabyte. At a data rate of 10kbps, it would take over 10 minutes to transfer the file. Moreover, considerable information on the WWW is in the form of images. Processing this information will require improved display capability in both size and quality. As usage of these large files becomes more prevalent, the need for higher data rates to send even more data will escalate.The need for video/still image transmission in addition to reception will also grow.

Another major influence on wireless communications systems in the future could be political or governmental regulation. Setting a standard for a wide geographic region by government action, as was done for GSM in Europe, was the single biggest reason for its growth. Although the analog AMPS system offered better audio quality, and was significantly lower in cost, the impact of government regulating bodies around the world was underestimated. As a result, GSM has become the largest cellular service.

While the definition of third generation cellular is intended to address the needs of the future by providing mulitple services, there will still be dedicated short range communications devices. Many of these will fall into the categories of man to machine and machine to machine communications links. For example, at the 1998 Consumer Electronics Symposium, devices to transmit CD quality audio from room to room wirelessly, TV, VCR, or stereo remote control signals using RF, video and audio from a PC to a TV, and signals from personal property for security were demonstrated. Small transponders to attach to objects such as car keys for location, and to broadcast remote data such as the temperature of a pool or spa were also displayed. As the price of a wireless communication transceiver is reduced, more of these types of devices primarily for the home will become new products.

3. 3RD GENERATION CELLULAR (3G)

At the World Administrative Radio Conference (WARC) of the International Telecommunication Union (ITU) in 1992, global bands between 1885-2025 MHz and 2110-2200 MHz were identified for Future Public Land Mobile Telecommunication Systems (FPLMTS) which has been renamed IMT-2000 (International Mobile Telecommunications 2000). [4] The allocations included the existing 1980-2010 MHz and 2170-2200 MHz bands for satellite communications. Besides voice, 3G will provide high speed data and multimedia capability. The goals of IMT-2000 are to: 1) integrate residential, office, and cellular services, 2) provide speech quality comparable to land line, 3) seamless global radio coverage offering a wide range of services 4) data rates of 144kbps (recent discussion has suggested that this should be increased to 384kbps) that should be extended to 2Mbps in microcellular coverage areas with the possibility of future burst rates to 20Mbps, and 5) creation of direct satellite access. There have been efforts in Europe, Asia, and the United States to address these goals. In Europe, ETSI has specified the Universal Mobile Telecommunications System (UMTS) and has supported the RACE (Research into Advanced Communications in Eurpoe) program. Standardization work in Japan is being done by ARIB (Association of Radio Industries and Businesses) and in South Korea by ETRI (Electronics and Telecommunications Research Institute). In the United States, the US-PCS system occupies a portion of the frequency band identified for IMT-2000. However, an enhanced IS95 standard has been announced to accomodate IMT-2000. In order to provide for the goals of the IMT-2000 communications systems, there have been two primary multiple access schemes proposed 1) Wideband CDMA (W-CDMA) and 2) Time division CDMA (TD-CDMA). At a January 1998 meeting of ETSI, a compromise agreement was reached that draws on both of these technologies. The new standard is called UMTS Terrestrial Radio Access (UTRA). The technology is basically the W-CDMA approach modified to ensure that it works with GSM, provides for FDD/TDD dual mode, and fits into the US spectrum.

For a 3G cellular system, simply providing a high data rate will not be sufficient. It will also be necessary to handle various data rates on demand and to realize effective packet data transport as the transition from circuit switched to packet switched data occurs. Packet switched data will provide better utilization of the available bandwidth and thus a better solution to the mixed traffic (voice, data, video) proposition. The quality of service will be differentiated on the basis of latency and negotiated by the handset. A critical element of the delivery of information will be end to end security including authentication and authorization.

Wireless ATM (WATM) recently has been considered as the transfer mode suitable for delivery services requiring high data rate wirelessly [5]. The technical feasibility to provide wireless extensions to the wired ATM system has been shown [6]. A recent agreement has been made such that the 5GHz band be developed first providing at least 25Mbps data rates [7]. However, this approach does not satisfy the IMT-2000 vision in two respects: 1) mobility will be limited due to high data rates and 2) operation would occur in the 5GHz band as opposed to the 2GHz band. While WATM technology is required to interface with the PSTN, it is also critical to the support of the internet community. Because the Internet Protocol has more connectivity than any other system, application developers will continue to migrate to this standard. The next version of the Internet Protocol (IP V6) provides class of service and quality of service capabilities and will need to be supported.

4. RECEIVER DESIGN

A typical transceiver block diagram is shown in Figure 2. The received signal for the antenna is processed through alternating selectivity and gain blocks prior to the first mixer. These stages establish the receiver sensitivity, intermodulation performance, and provide attenuation to the image and half IF (intermediate frequency) spurs. The receiver signal is frequency translated to a first IF that typically ranges from 45-110 MHz. The injection (or LO signal) for the mixer is provided by a frequency synthesizer. The frequency synthesizer produces an output frequency proportional to the input crystal oscillator which sets the overall frequency stability of the radio. The first IF is filtered, typically by a crystal filter with a Q ranging from 500 to 10,000 depending on the application, to provide image protection for the second mixer and some adjacent channel protection. The second mixer frequency translates the signal to a second IF. This frequency is typically either 455 KHz or 0 Hz. The second mixer is followed by integrated selectivity which forms the bulk of the receiver adjacent channel selectivity protection. IF's operating at

455KHz are processed through a bandpass ΣΔ converter which feeds a digital baseband processing IC that is either application specific or a general purpose DSP. Zero IF's perform the selectivity via active continous time filters such as OTA-C filters. The output of the continous time filter is either A/D converted to feed a digital baseband processor or is processed using analog demodulation and signal processing techniques. The baseband function is highly integrated onto one or two IC's dependent upon whether the demodulation and audio signal processing are implemented in the analog or digital domain. The output of the baseband procesing is applied to an audio amp which drives the loud speaker.

5. TRANSMITTER DESIGN

The transmitter provides gain and signal conditioning to a frequency synthesized source signal. For duplex systems, a synthesized signal for both the receiver and transmitter is required. For FDD systems, the signals are required simultaneously and can be generated by either two synthesizers or by using an offset mixer to generate the second signal in the case where the transmit and receive pairs have a fixed offset. For TDD systems where the transmit and receive signals are identical, only one frequency synthesizer is required. The succeeding stages add gain to achieve the specified output level. These stages determine the Power Amplifier (PA) efficiency, spectral purity, and linearity of the transmit signal. The PA power level and efficiency will dictate the talk time achievable.

6. TRANSCEIVER INTEGRATION

In spite of today's high levels of integration, a two way radio or cellular phone requires a total of about 450 parts to complete the radio design. The discrete parts consist primarily of resistors, capacitors, and inductors. Roughly 1/3 of the parts are associated with the frequency synthesizer, 1/4 with the receiver RF and IF sections, and 1/5 with the transmitter. In each of the RF/IF, frequency synthesizer, and transmitter sections, 30%-50% of the cost is due to the external, non-integrated components. In addition to their cost, they consume roughly 35- 45% of the board area. In order to reduce the external part count significantly, a combination of clever system/circuit design and IC processes designed specifically for RF signal processing will be required. Historically, semiconductor wafer processes have not been optimized for RF performance due to the small market size. However, due to the growth in the wireless communications market, the situation has changed such that it now makes sense to consider an RF specific process. For this process, there are 3 key attributes: 1) integrated passives, 2) improved isolation, and 3) operation to 5-6 GHz. In the next section, each of these attributes will be discussed in detail.

7. OPTIMIZED RF PROCESS

Integrated resistors are typically included in most analog processes. It is particularly desirable to provide a high value sheet resistance (2 - 5kΩ/sq) resistor to use for current setting in low current designs. Additionally, a low value sheet resistance (50-100Ω/sq) should be provided for degeneration purposes. Each of these resistors should have a 3σ make tolerance of 10%-20% and a 3σ matching of < 1%. A positive temperature coefficient (TC) is desirable for use in a bandgap type circuit. Parasitic capacitance should be minimized, which suggests a poly resistor, in order to maximize circuit performance.

Three types of integrated capacitors are required: 1) moderate value ($3 - 6\ ff/\mu^2$) for analog filtering, 2) high value ($> 100ff/\mu^2$) for local supply bypassing, and 3) voltage variable capacitors such as varactors for tuning. The capacitor for analog filtering should have a low voltage sensitivity (< 100ppm/V), a small parasitic capacitance (<10% of desired capacitance), a low TC (< $100ppm/^oC$), a 3σ absolute value variation of < 10%, and a 3σ matching of < 0.1 %. The high value capacitor (HVC) function is to provide local bypassing at each subcircuit supply and ground connection, much the same as implemented on a PC board. The secondary parameter of interest for the HVC is a self resonance at the RF/IF and harmonics of RF/IF signals. The HVC could also be utilized as a DC blocking capacitor. A typical use of a varactor would be as the tuning element for an integrated VCO. Typical VCO's with varactor tuning exhibit a sensitivity of 5-10 MHz/V depending on the bandwidth covered and supply voltage available. The required Q of the VCO is in the range of 50-100. As the sensitivity of the VCO is increased, it becomes more difficult to achieve the sideband noise performance of the VCO. In order to alleviate this problem, which gets significantly worse at the lower supply voltages, it is likely that the system/circuit design must provide for switching of the other elements in the VCO tank circuit.

Integrated inductors are required to provide RF filtering, matching, and tuning. Integrated inductors are key to integrating the RF front-end selectivity and the VCO tank functions. For these applications, inductance values from 1-10 nH are adequate. For the VCO, a Q of > 20 at 1 GHz is necessary. High Q can only be achieved by utilizing a thick, low resistivity metal like plated copper to minimize ohmic losses coupled with a structure that minimizes losses in the substrate. The structures required to minimize loss in the substrate are either a toroidal 3 dimentional structure [8] or a spiral inductor placed over a high resistivity (5 - 10Ω-cm) substrate. One way to achieve the necessary device performance while maintaining a high resistivity substrate is to utilize a TFSOI technology.

It is possible with today's .35μ technology to integrate onto a single BiCMOS IC all of the receiver, frequency generation, and baseband signal processing functions in a reasonable die size. However, due to insufficient isolation, primarily between the clocking signals of the digital logic and the very sensitive RF circuitry, this degree of integration has not been achieved for a cellular phone application. Figure 3 shows simulated isolation data for several structures including a p+ guard ring, SOI with the handle floating and grounded, and a p+ guard ring with full junction isolation compared to the case with no isolation [9]. It can be seen that all isolation approaches improve upon the non-isolated case and that substantial improvements below 1GHz can be realized by the appropriate choice of isolation technique but at and above 1GHz all of the improved isolation techniques are similar in performance. The majority of existing services, and planned future services, operate in bands at and above 1GHz. An additional 30db of isolation is required beyond what can be achieved today. To obtain this level of performance, innovative isolation techniques will be required. It is difficult to compare the isolation results achieved by researchers due to the measurements being made on a variety of structures using a variety of methods. The result is that the absolute, as opposed to relative, magnitude of isolation reported is not useful. Therefore, a further enhancement to the study of isolation would be a semiconductor industry-wide agreed upon structure and method of measurement for evaluation .

In addition to these technology requirements, there is a need for high performance MOSFET's. There is considerable debate as to whether a single chip transceiver can be implemented in CMOS or whether BICMOS is required. Substantial efforts are being expended in academia [10,11] researching an all CMOS approach. Bipolar technologies have historically enjoyed an advantage over CMOS for high frequency operation. It appears that with the development of the Si-Ge transistor [12] that this will remain the case for at least the next five years. However, for operation to 1GHz, .25μ CMOS is capable of acceptable RF performance today. Bipolar transistors offer other advantages over CMOS devices which provide benefit at baseband: 1) higher gm, 2) better matching, 3) lower 1/f noise, and 4) lower offset voltage. Particularly as designs move to lower voltages, the benefits of higher gain per stage and better matching can not be ignored. For zero IF receivers, the benefits of lower 1/f noise and lower offset voltage cannot be ignored. For these reasons, wireless communications products introduced before the year 2000 will still contain bipolars.

New spectrum allocations for wireless communications continue to occur at higher frequencies. Last year the FCC allocated 300 MHz of spectrum between 5-6GHz. This spectrum aligns with other allocations around the world. In order to take advantage of this spectrum in a cost effective manner, silicon technology must be developed. One candidate device for 5-6GHz operation is a Si-Ge bipolar transistor. Devices have been demonstrated with an f_τ of 50 GHz. This device has been integrated into a standard IBM CMOS flow. A Si-Ge transistor, or other bandgap engineered transistor, will likely be a key device for future wireless communication integrated circuit design.

8. CRITICAL RF CIRCUITS

During the transistion from second generation to third generation cellular, as well as for other wireless communications applications, there will be a need for multi-band, multi-mode transceivers to provide multiple services. Moore's law predicts that the number of transistors on a chip will double every 18 months. These transistors will be used in part to enhance the existing feature set by adding capabilities such as video. There will also be a drive to utilize these transistors to push the digital circuitry from the baseband function towards the antenna. However, the specification of most of today's systems require 100-120db of dynamic range. For an A/D to be attached to the antenna, it would need to be a 17-20 bit A/D convertor operating at a sample rate of at least twice the information bandwidth. It would also need a sampler having a time jitter commensurate with the sideband noise requirement of a system implemented with a VCO used for frequency translation. For a subscriber unit, the available technology is far from meeting these accuracy requirements. Furthermore, once the accuracy levels are achieved, it is likely it would be at least another five years before the power consumption of this approach would be acceptable.

The challenge of building a multi-band, multi-mode transceiver is to minimize duplication of circuit functions specific to each mode. For baseband processing, this can be accomplished by using a common DSP/μC, providing for the maximum memory of two or more modes, and duplication of some low level DSP/μC peripherals such as timers. The software can be either over-the-air down-loadable or provided via a SmartCard. For the RF circuitry, the challenge is significantly more difficult.

Utilization of the same antenna for two or more RF bands will result in roughly a difference of 10dB antenna gain for an octave change in RF frequencies. This will result in a reduction of talk distance for the non-optimized band. Referring to Fig 2, the front end processing through the first mixer of the receiver will be unique to each RF band. It is possible to design broadband active circuits for LNA's and mixers to cover multiple RF bands. However, the frequency selective block, the RF match, and RF tuning passive components will need to be switchable and duplicated. In addition to the RF frequency, the difference in bandwidth requirements will dictate the degree of reuse achievable.

Once the signal is at an IF, the circuits are at least fixed tuned and only differences in bandwidths between the two different modes needs to be accounted for. Outside of the crystal filtering, these differences can typically be handled by switchable integrated components. For wideband systems like GSM, with IF bandwidths approaching 200KHz, bandpass $\Sigma\Delta$ architectures are not preferred due to power drain considerations. Therefore, for a primary narrowband transceiver adding a wideband service, the receiver backend approach will likely be of a zero IF type to provide for integration of the selectivity for both modes.

The solution to minimize the duplication of circuitry is to eliminate the conversion from RF to the 1st IF. This can be accomplished by use of a direct conversion receiver. To accomplish the LNA and mixer functions for a direct conversion receiver, the f_τ of the process must be 10-15 times the highest RF frequency to be converted.

For the transmitter, the primary technical challenge is the design of the RF PA. The main difficulty is acheiving efficiency in a dual mode PA that is comparable to the efficiency of a PA designed specifically for each mode. The worst case scenario is adding a linear PA to accommodate a modulation format like $\pi/4$ QPSK that has a peak to average ratio of 2-3dB to a constant envelope class C PA used for a modulation format like FM. A primary requirement for the PA devices will be the choice of a device that can handle the peak power requirement at all RF frequencies. Like the receiver, it is possible to design broadband active devices but the RF matching and tuning elements will require switchable and duplicated passive discrete components.

For 3G cellular systems, many of the previously mentioned technology issues apply. There will, however, be an increased burden placed on the baseband signal processing elements in order to maintain the 10^{-3} BER required for voice communications and the 10^{-6} BER required for data communications. Technologies to mitigate interference and improve effective receiver sensitivity by utilizing new modulation formats, smart antennas, and/or adaptive data rates will need to be developed. With the selection of a CDMA access scheme, transmitter power control and soft handoff algorithms will need to be enhanced. The increased computational requirements and increased data rate will require memory in excess of 2 Mbit which will place a premium demand on embedded memory . For high tier products, this embedded memory will have to become embedded DRAM to minimize die size and cost.

9. CONCLUSION

This paper has addressed some of the trends in both the market and technology that can be expected for wireless communications devices into the 21st century. Although enhanced data rate has been discussed and proposed for years, the growth of the Internet has brought into focus the need for broadband wireless communications. While the 3G standards attempt to satisfy the need for the ubiquitous wireless communications device, pro-

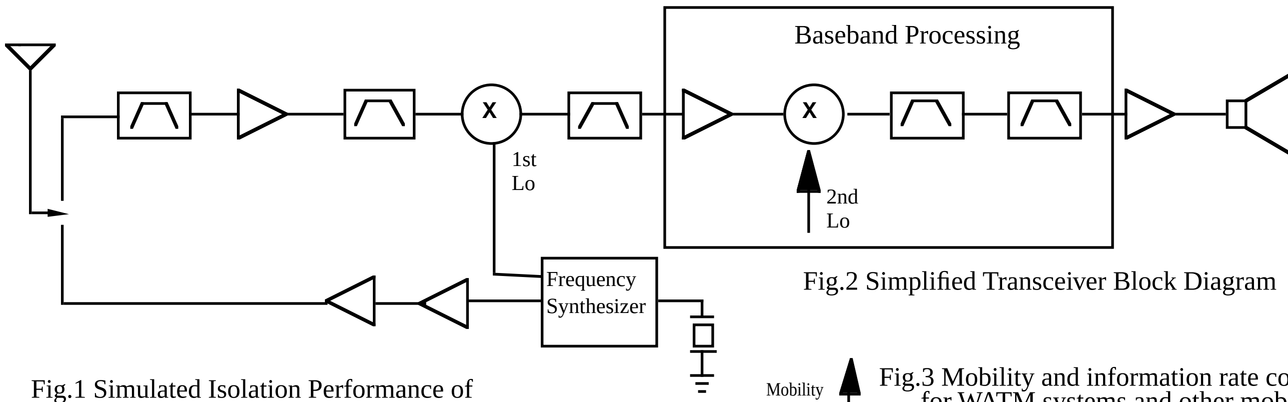


Fig.2 Simplified Transceiver Block Diagram

Fig.1 Simulated Isolation Performance of various Isolation Techniques

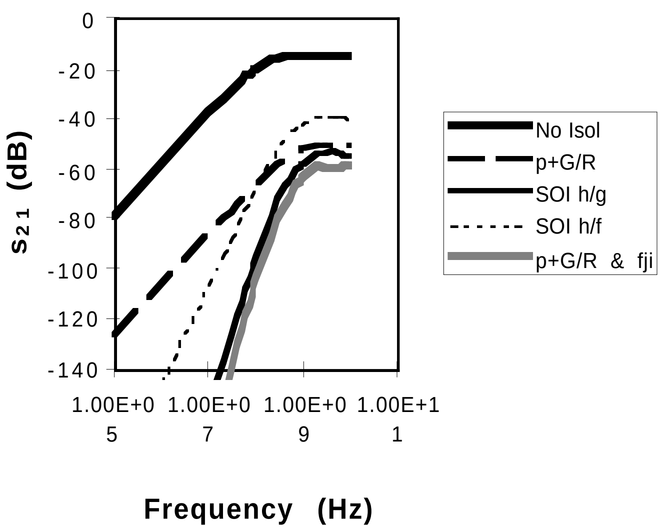
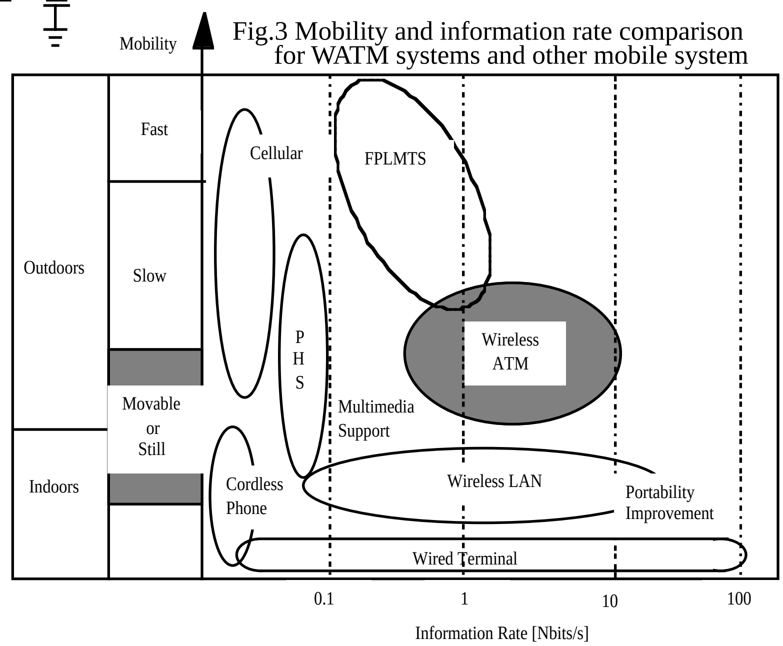


Fig.3 Mobility and information rate comparison for WATM systems and other mobile system



viding voice and broadband data communication anytime and anywhere, there are many technical and political issues yet to be solved. Therefore, a transition period will exist where multi-band, multi-mode transceivers will be built to provide enhanced services and enhanced coverage compared to existing cellular systems. These systems address the in-vehicle needs of the consumer but large growth opportunities still lie in the relatively untapped home and office environments. It is expected that increased man to machine and machine to machine wireless communications applications will be developed for these environments. It has been proposed that an IC process be developed specifically for RF signal processing. Wireless communications will continue the fast pace of growth into the 21st century by upgrading the level of service and adding new applications while providing the unique benefit of mobility.

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