The Impact of Emerging "4G" Systems on the Performance and Complexity Requirements of RFICs - Invited Paper

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Abstract — **Although 4G systems are many years from being deployed on a widespread basis, there is an active ongoing worldwide effort to develop the requirements of these proposed new systems. The standards and goals of these new systems are still in considerable flux, although some overall trends have emerged. This paper will present an overview of a variety of proposed schemes, and their issues for RFIC implementation at the handset level.**

I. INTRODUCTION

The dire condition of the worldwide telecommunications industry has not prevented many research groups from beginning development of fourth-generation (4G) wireless systems. There are no approved standards yet for these systems, and even the performance goals are in considerable flux. Nevertheless, several key features are coming into view.

Fundamentally, the goal of these networks is to be able to deliver at least 50 MBps (NTT DoCoMo has proposed 200Mbps [1]) to a mobile user using an IP-based network. Some of the highlights of these still tentative proposals are: support for streaming, multicasting, and generic data, use of smart/adaptive antennas/MIMO, downloads of 5-20 Mbps even when traveling 200 kM/hr, wideband OFDM/multi-carrier modulation, multi-standard interface (3G/4G/802.11/GPS/Bluetooth), and an IP-centric network. The evolution of these systems over the next decade is illustrated in Figure 1 for the case of the IMT-2000 based 3G systems [2]. The spectrum available for these 4G systems has not been allocated yet, and the current plan is for this to be accomplished at the World Radio Congress in 2006 (WRC2006). So many of the physical aspects of these new devices have not been determined yet.

This paper will summarize some of the major features that are emerging in the description of these proposed 4G systems. These new systems will present new cost and performance challenges in the RFIC realm, and the next sections will summarize some of the key parameters in these new systems.

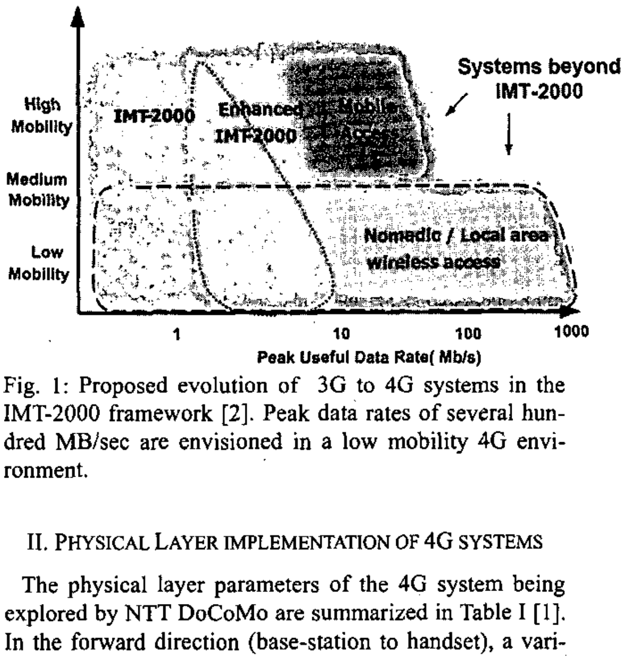

Fig. 1: Proposed evolution of 3G to 4G systems in the IMT-2000 framework [2]. Peak data rates of several hundred MB/sec are envisioned in a low mobility 4G environment.

II. PHYSICAL LAYER IMPLEMENTATION OF 4G SYSTEMS

The physical layer parameters of the 4G system being explored by NTT DoCoMo are summarized in Table I [1]. In the forward direction (base-station to handset), a variable spreading factor orthogonal frequency and code division multiplexing (VSF-OFCDM) scheme was chosen for its high spectral efficiency, flexibility, and insensitivity to multi-path effects. If 64QAM modulation is employed, with R=3/4, the link is capable of reaching a peak data transfer rate of over 300 Mbps. From a radio-frequency hardware perspective, this modulation approach represents a *very* formidable challenge for the base station power amplifier, which will have to contend with a very high peak-to-average waveform along with a very wide bandwidth. This may force deployment of relatively low power base stations – at least initially – that provide local coverage in certain high data rate "hot spots."

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Table I: Major 4G Radio Link Parameters Proposed by NTT DoCoMo [1].

(a) Forward Link

Wireless Access	VSF-OFCDM
Bandwdith	101.5 MHz
Number of Sub-Carriers	768
Sub-carrier freq. spacing	131.84 kHz
Spreading factor	768 chips/sub-carrier
Data Modulation	QPSK,16QAM,64QAM
OFCDM symbol duration	9.259 μsec
Frame length	0.5 msec
Channel Coding/Decoding	Turbo-coding (R=1/2,3/4, K=4)

(b) Reverse Link

Wireless Access	MC/DS-CDMA
Bandwdith	40 MHz
Number of Sub-Carriers	2
Sub-carrier freq. spacing	20 MHz
Chip rate	16.384 mcps
Spreading factor	1-256
Data Modulation	QPSK,16QAM,64QAM
Roll-off factor	0.22
Frame length	8192 chips
Channel Coding/Decoding	Turbo-coding (R=1/2,1/16, K=4)

The inherent asymmetry of most applications allows the reverse link (handset to base-station) to operate at somewhat lower data rates. In this case, a direct-sequence CDMA (DS-CDMA) approach along with a Rake receiver in the base station is proposed. This approach allows for a much lower peak- to-average ratio in the transmitter power amplifier than the VSF-OFCDM case, and hence higher power-added efficiency in the handset power amplifier. Nevertheless, the bandwidths (20 MHz per carrier) and modulation scheme (up to 64QAM) are again far more challenging than today's handset power amplifiers.

II. Network Layer Implementations of 4G Systems

One consistent theme of many 4G proposals is that future mobile devices should be able to roam across multiple networks and multiple air interfaces, and be able to *choose* the network connection that best fits its needs at any time. This might be a traditional 3G/4G network, a 2.4 GHz or 5 GHz WLAN interface, or even a higher bandwidth PAN depending on the circumstances.

For very low mobility personal area network applications, data rates in excess of a Gb/sec are desirable for a variety of graphics intensive applications. Several other possible physical implementations of these high data rate systems are currently being explored as part of a future 4G network. These include Ultra-WideBand (UWB) systems [3] and millimeterwave communications at the 60 GHz or higher band [4]. The later is especially attractive for very short-distance high data rate communications applications, due to the large amount of generally unoccupied spectrum.

One example of this vision of a network architecture that spans many possible physical layers is the Ericsson *Always Best Connected* (ABC) project [5], which aims to allow wide area wireless operators to leverage the proliferating use of high-speed local area networks and other wide area networks while preserving seamless connectivity.

At the network level, this presents a host of interesting challenges, including handoff requirements, the nature of Quality of Service provisions and how are they guaranteed if the user roams across multiple networks, the optimum form of mobile-IP, and establishing "differentiation" between services offered by different operators.

III. "Software-Defined Radio" Performance Issues

A transceiver architecture that addresses the wide dynamic range requirements of these future multi-standard implementations will necessarily heavily rely on extensive digital processing for many aspects of the system. This naturally leads to a discussion of "software defined radios," and the increasing use of digital signal processing techniques in transceiver design.

If an IF-sampling approach is employed, the digital-downconverter (DDC) will perform the digital down-conversion, filtering and sample-rate reduction. In the transmit path, digital-upconverters (DUCs) are used for tasks like e.g. resampling, pulse shaping and digital up-conversion. These tasks will change, depending on the standard in use at any given moment.

At the RFIC level, the challenge will be to accommodate these various standards on a small number of monolithic IC's. In the ideal case, shown in Fig. 2, the entire multi-band transceiver would reside on a single highly integrated die. In fact, the approach of using multiple separate receivers and transmitters wastes a large amount of die area – since only one transceiver is used at any time. Therefore, transceiver architectures that can tune across multiple bands are highly desirable.

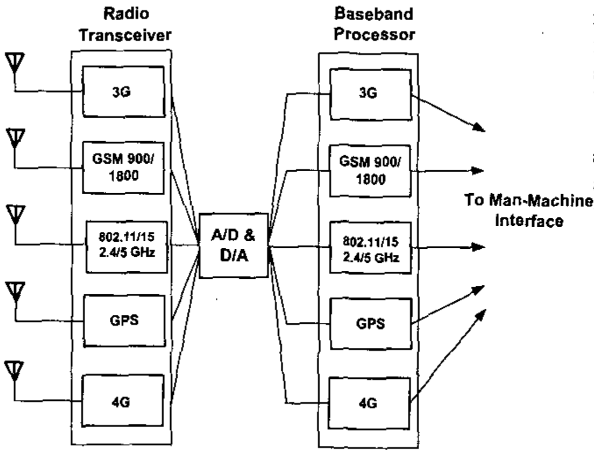

Fig. 2. Block diagram of multi-standard transceiver for 4G applications. The current trend for multiple standards in a handset will accelerate in these new systems.

As Figure 2 shows, the "pressure point" in such a future system becomes the A/D converter. A recent study on the possibility of a "software-defined" multi-mode GPRS/WCDMA/802.11A transceiver demonstrated that a 14-bit 80 Msps ADC, with a power consumption of less than 50 mW is required for this application [6]. Given the fact that the power consumption *per Msample/sec* halves roughly every other year, this level of performance is at least five years in the future from reality [7]. The ADC requirements for the 4G data rates are even more aggressive. This gap between the performance of ADCs and the requirements of the software-defined radio has historically limited the application of this approach. Clearly, a "breakthrough" in ADC performance would remove a significant barrier to the implementation of these multi-standard systems.

IV. "SMART" ANTENNA SYSTEMS

Antenna "diversity" techniques are typically defined as those having multiple independent channels between the transmitter and receiver. The mathematical techniques for accomplishing diversity on reception are fairly well-known. However, to date they have not been widely implemented (except for the simplest case of selection diversity). This is because the analog and digital hardware requirements for implementing sophisticated diversity schemes are typically prohibitively complex, although this is expected to improve in 4G systems.

The use of multiple receive antennas (also known as receiver diversity) is fairly straightforward to analyze. In its simplest form, multiple copies of the transmitted stream are independently received, and can be effectively combined using appropriate signal processing techniques to improve the overall performance. In addition, multiple antenna techniques can be employed for beam steering applications and to reduce interference from neighboring users, as shown conceptually in Figure 5.

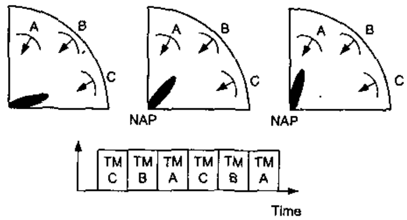

Fig.3. Interference suppression techniques using multiple receive antennas. The interference at the network access point due to the presence of other users is reduced due to the beam steering of multiple phased antennas.

Receive diversity is commonly implemented today in low-cost wireless LAN and cellular systems using *selection diversity*, where the antenna with the highest received signal power is chosen. A more promising and challenging approach is the use of maximal ratio-combining, which provides a near optimal solution assuming that the channel is stationary and that its characteristics are well-known [8]. In this case, the signals from each antenna are essentially weighted by the received signal-to-noise ratio of that path. It can be shown that this technique is optimum in the sense that it maximizes the overall received SNR, although other combining techniques have advantages under differing channel assumptions. With QPSK modulation, the gain in SNR using four receive antennas can be as large as 15 dB [9]. The technique is somewhat sensitive to channel estimation errors, which is itself dependent on the received SNR.

Detailed knowledge about the channel is crucial to achieving the theoretical gains associated with the maximum-ratio power combining (MRC) approach. This is especially true in the multi-path environment encountered by a typical WLAN. The assumption of "perfect" knowledge about the channel falls apart quickly under real world conditions. For example, pilot tones on the 802.11a signal can be used for channel estimation purposes, but the correlation of the pilot tone channel response to the data channel response is imperfect. In addition, the estimate of the magnitude and phase shift of the channel is itself imperfect. Training symbols (in the preamble) can also be used to gain information about the channel.

The RF/analog architecture used to implement this power combining scheme has several different possible variations. The most straightforward is shown in simplified form in Figure 11 [10]. In this case, the phase shift is performed at RF frequencies using externally variable phase shifters to provide for the appropriate phase shift, and IF externally controllable variable gain amplifiers to provide the appropriate tap weighting. This architecture has several advantages, since each path can be independently varied in both gain and phase prior to combining. Recent results on this approach from Toshiba [10] demonstrate a significant improvement using this technique.

The disadvantage of this approach derives from the fact that the power combining at IF removes the information from each individual antenna; after that point, multi-path information is no longer resolvable. If the tap weights are ideal, this should not be a limitation, but it leaves little room for subsequent performance gains in the DSP. Another disadvantage is that the IF channel selection filters may have to be implemented using relatively expensive SAW filter technology.

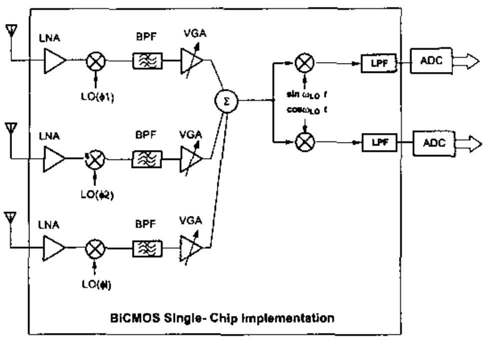

Fig. 4 Multiple antenna combining at the IF level for 5 GHz OFDM system [10].

V. Conclusion

Although it is still several years from being deployed on a large scale, fourth-generation wireless technology is currently being developed on a worldwide basis. The key aspcts of the technology will be the ability to roam across multiple networks and having access to data at rates of approximately 100MB/sec. This will require several innovations at the RF level, including the economical development of multiple antenna techniques, mutli-standard transceiver architectures, and dramatic advances in low-power data converter technology.

VI. Acknowledgement

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