Post-Cellular Wireless Networks
Outline

① Flashback
② Coming Up: 5G
③ A World Without Cells?
① Flashback
“I do not think that the wireless waves I have discovered will have any practical applications”
2nd Breakthrough

Nikola Tesla

Guglielmo Marconi


TITANIC SINKS FOUR HOURS AFTER HITTING ICEBERG: 866 RESCUED BY CARPATHIA, PROBABLY 1250 PERISH; ISMAY SAFE, MRS. ASTOR MAYBE, NOTED NAMES MISSING
4th Breakthrough

Claude Shannon

Bell Laboratories
5th Breakthrough

“There’s plenty of room at the bottom”
R. Feynman

FAIRCHILD

intel

TEXAS INSTRUMENTS

A persevering prediction
Number of transistors in CPU

MOORE’S LAW DEFINED

10^10

10^8

10^6

10^4

10^2

1

1960 70 80 90 2000 10 14

FIRST COMMERCIALY PRACTICABLE INTEGRATED CIRCUIT

AT THIS SITE IN 1959, DR. ROBERT NOYLE OF FAIRCHILD SEMICONDUCTOR CORPORATION INVENTED THE FIRST INTEGRATED CIRCUIT THAT COULD BE PRODUCED COMMERCIALLY. BASED ON "PLANAR" TECHNOLOGY, AN EARLIER FAIRCHILD BREAKTHROUGH, NOYLE'S INVENTION CONSISTED OF A COMPLETE ELECTRONIC CIRCUIT INSIDE A SMALL SILICON CHIP. HIS INNOVATION HELPED REVOLUTIONIZE "SILICON VALLEY" SEMICONDUCTOR ELECTRONICS INDUSTRY AND BROUGHT PROFOUND CHANGE TO THE LIVES OF PEOPLE EVERYWHERE.

CALIFORNIA REGISTERED HISTORICAL LANDMARK NO. 1000
PLACED BY THE STATE DEPARTMENT OF PARKS AND RECREATION IN COOPERATION WITH FAIRCHILD SEMICONDUCTOR CORPORATION, AUGUST 9, 1991.

294x524 5th Breakthrough

313x534 “There’s plenty of room at the bottom”

305x485 R. Feynman

427x462 FAIRCHILD

541x485 intel

427x462 TEXAS INSTRUMENTS

310x485 A persevering prediction

498x389 Number of transistors in CPU

667x457 MOORE’S LAW DEFINED

163x392 FIRST COMMERCIALY PRACTICABLE INTEGRATED CIRCUIT

359x377 AT THIS SITE IN 1959, DR. ROBERT NOYLE OF FAIRCHILD SEMICONDUCTOR CORPORATION INVENTED THE FIRST INTEGRATED CIRCUIT THAT COULD BE PRODUCED COMMERCIALLY. BASED ON "PLANAR" TECHNOLOGY, AN EARLIER FAIRCHILD BREAKTHROUGH, NOYLE'S INVENTION CONSISTED OF A COMPLETE ELECTRONIC CIRCUIT INSIDE A SMALL SILICON CHIP. HIS INNOVATION HELPED REVOLUTIONIZE "SILICON VALLEY" SEMICONDUCTOR ELECTRONICS INDUSTRY AND BROUGHT PROFOUND CHANGE TO THE LIVES OF PEOPLE EVERYWHERE.

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Dozens of new base stations would have to be installed and cut into service at the same moment. Hundreds of radios in the old base stations would have to be moved and retuned. It was a costly, labor-intensive process and promised to be very difficult logistically.

While drawing such a configuration, it occurred to me that this massive disruption was being created to achieve an incremental increase in system capacity. At that moment, the larger cells were serving almost the entire traffic demand. If we retained the existing cells as a continuous “underlaid” grid providing almost all the needed capacity, we could add a few “overlaid” smaller cells “here and there,” with only a few channels, to provide the small amount of incremental capacity we needed. Those few channels could continue to be used at the original base stations for mobiles that were in the inner portion of the cell (in effect, for a smaller cell that was co-sited with the larger cell). Calls that left these new isolated cells could be handed off to the underlaid grid, which would still provide geographically continuous coverage. Over time, more new base stations would be added, and more channels would gradually be moved into those new base stations until the old grid was finally replaced, but the process would be gradual and manageable. This eliminated the logistic problems of cell splitting and reduced the number of cells that were needed at most points in growth rather dramatically. Simulations using Jim O’Brien’s MultiCell simulation showed that the average number of cells in a growing system (and thus the average system cost) were reduced by more than 50 percent. That simple idea later became one of AT&T’s most sought after patents in cross-licensing agreements [10].

SYSTEM TRIALS AND COMPATIBILITY STANDARDS

As the system design progressed toward completion, it became necessary to demonstrate that AMPS would provide both the excellent service and the spectrum efficiency that had been promised. This sort of demonstration would be a feature of any development program, but amid the political debates of the time it led to new controversies and delays. To demonstrate real service, we would need a large coverage area, and to demonstrate the proper working of the system for the largest capacity we would need to use small cells. Putting the two objectives together would create a trial with hundreds of cells, which was economically infeasible, so AT&T proposed to separate the demonstration into two trials. The Chicago Service Trial would demonstrate real service in a startup configuration, with production equipment and several thousand subscribers. A cellular testbed in Newark would simulate operation in a few 1-mi cells, surrounded by six interfering cells several miles away. The coverage maps for the Chicago and Newark trials are shown in Fig. 3.

Objections were raised to the proposed trials, in particular because they would not demonstrate production equipment in the smallest cells. The FCC agreed with the objectors and denied permission for the trials. AT&T appealed, and the FCC eventually reversed their decision, granting approval for the Chicago and Newark trials on March 10, 1977, but a full year was lost in the appeal process. The FCC also granted approval to Motorola to operate a trial in the Washington, DC/Baltimore area. A Motorola team led by Marty Cooper had created the first truly portable handheld cell phone, called Dyna-TAC, and service for portable handsets would be the focus of that trial. Dyna-TAC was large and heavy by modern standards (about the size and weight of a brick), but it represented a significant breakthrough in portability. It was a major step in the evolution of cellular from a telephone in a car to the truly “personal” communication service we enjoy today.

Installation of the equipment and facilities for AT&T’s Chicago trial [11–13] was the responsibility of a large team led by Jim Troe. The system used 10 cells to cover 3000 mi\(^2\), with a switching center at Oak Park and an operating center in Evanston.
Flashback

Relative Subscriptions

1990  2000  2010  2020  2030
Area Capacity

\[
\frac{\text{bits/s}}{\text{Km}^2} = \left( \frac{\text{bits/s/Hz}}{\text{cell}} \right) \cdot \left( \frac{\text{cell}}{\text{Km}^2} \right) \cdot [\text{Hz}]
\]

Spectral Efficiency

Cell Density

Bandwidth
Compounded Gain in Wireless Area Capacity

- Cell Density \(\times 1600\)
- More Bandwidth \(\times 25\)
- Spectral Efficiency \(\times 10\)
- Other \(\times 2.5\)

\(\times 10^6\)

Martin Cooper
\[
\frac{\text{bits/s}}{\text{Km}^2} = \frac{\text{bits/s/Hz}}{\text{cell}} \cdot \frac{\text{cell}}{\text{Km}^2} \cdot [\text{Hz}]
\]
\[
\approx \frac{b/s/\text{Hz}}{\text{cell}} \cdot \frac{\text{cell}}{1000 \text{ users}} \cdot 500 \text{ MHz}
\]
\[
= 500 \frac{\text{Kb/s}}{\text{user}}
\]
MIMO (Multiple-Input Multiple-Output)

\[ y = Hx + n \]
Coming Up: 5G
Overall mobile data traffic is expected to grow to 24.3 exabytes per month by 2019, nearly a tenfold increase over 2014. Mobile data traffic will grow at a CAGR of 57 percent from 2014 to 2019 (Figure 1).

The Asia Pacific and North America regions will account for a little over half of global mobile traffic by 2019, as shown in Figure 2. Middle East and Africa will experience the highest CAGR of 72 percent, increasing 15- to 16-fold over the forecast period. Central and Eastern Europe will have the second highest CAGR of 71 percent, increasing 14- to 15-fold over the forecast period. Latin America and Asia Pacific will have CAGRs of 59 percent and 58 percent, respectively.

Coming Up: 5G
What Will 5G Be?

Jeffrey G. Andrews, Fellow, IEEE, Stefano Buzzi, Senior Member, IEEE, Wan Choi, Senior Member, IEEE, Stephen V. Hanly, Member, IEEE, Angel Lozano, Fellow, IEEE, Anthony C. K. Soong, Fellow, IEEE, and Jianzhong Charlie Zhang, Senior Member, IEEE

Abstract—What will 5G be? What it will not be is an incremental advance on 4G. The previous four generations of cellular technology have each been a major paradigm shift that has broken backward compatibility. Indeed, 5G will need to be a paradigm shift that includes very high carrier frequencies with massive bandwidths, extreme base station and device densities, and unprecedented numbers of antennas. However, unlike the previous four generations, it will also be highly integrative: tying any new 5G air interface and spectrum together with LTE and WiFi to provide universal high-rate coverage and a seamless user experience. To support this, the core network will also have to reach unprecedented levels of flexibility and intelligence, spectrum regulation will need to be rethought and improved, and energy and cost efficiencies will become even more critical considerations. This paper discusses all of these topics, identifying key challenges for future research and preliminary 5G standardization activities, while providing a comprehensive overview of the current literature, and in particular of the papers appearing in this special issue.

Index Terms—Cellular systems, energy efficiency, HetNets, massive MIMO, millimeter wave, small cells.

I. INTRODUCTION

A. The Road to 5G

In just the past year, preliminary interest and discussions about a possible 5G standard have evolved into a full-released by Cisco, we have quantitative evidence that the wireless data explosion is real and will continue. Driven largely by smartphones, tablets, and video streaming, the most recent (Feb. 2014) VNI report [2] and forecast makes plain that an incremental approach will not come close to meeting the demands that networks will face by 2020.

In just a decade, the amount of IP data handled by wireless networks will have increased by well over a factor of 100: from under 3 exabytes in 2010 to over 190 exabytes by 2018, on pace to exceed 500 exabytes by 2020. This deluge of data has been driven chiefly by video thus far, but new unforeseen applications can reasonably be expected to materialize by 2020. In addition to the sheer volume of data, the number of devices and the data rates will continue to grow exponentially. The number of devices could reach the tens or even hundreds of billions by the time 5G comes to fruition, due to many new applications beyond personal communications [3]–[5]. It is our duty as engineers to meet these intense demands via innovative new technologies that are smart and efficient yet grounded in reality. Academia is engaging in collaborative projects such as METIS [6] and 5GNOW [7], while industry is driving preliminary 5G standardization activities (cf. Section IV-B). To further strengthen these activities, the public-private partnership
\[
\left[ \frac{\text{bits/s}}{\text{Km}^2} \right] = \left[ \frac{\text{bits/s/Hz}}{\text{cell}} \right] \cdot \left[ \frac{\text{cell}}{\text{Km}^2} \right] \cdot [\text{Hz}]
\]

- **Spectral Efficiency** → **Massive MIMO**
- **Densification** → **Ultra Densification**
- **Bandwidth** → **New Spectrum**

Coming Up: 5G
Coming Up: 5G
Coming Up: 5G

New spectrum enabled by ultradensification
A World Without Cells?
A World Without Cells?
5  A World Without Cells?
5 A World Without Cells?
A World Without Cells?
⑤ A World Without Cells?
5 A World Without Cells?
“It’s dangerous to put limits on wireless”

Guglielmo Marconi, 1932