Future trends in wireless technology

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Our agenda
Forces, standards, technology

1. Introductions - help me to focus on your learning objectives
    - Quick introduction and your learning objectives for this course
2. Forces
    - How we look ahead & manage long-term research investments
    - Significant forces driving the industry's actions
    - Class dialogue
3. Standards
    - The role of standards in the wireless industry
    - Drivers/consequences – trade-off between stimulating adoption and limiting innovation
    - How to work in standards organizations
    - Class dialogue
4. Technology
    1. What we will see in the next 10 years…
    2. Class dialogue

How do we look ahead?

Direct observation is not possible…

- **Not possible to ask our customers what they will need in 10 years**
  - **We may not know who are customers will be in 10 years**
- **We still must plan our R&D investments today**
  - **Must be rational**
- **Look to the forces that constrain the industry**
  - **Not necessarily where the industry thinks it is going in the next 10 years**
- **Scenario planning builds a model around 5 force domains, categorized as trends and uncertainties identifiable from present conditions**
  - **Sociological**
  - **Technological**
  - **Economic**
  - **Environmental**
  - **Political**
- **A form of indirect observation**
  - Similar to a hidden Markov model
  - Forces are visible, but their consequences are invisible

$$f_0 \wedge f_1 \wedge f_2 \ldots \wedge f_N \rightarrow C$$

How do we analyze the forces?

Model building based on primary & secondary research

- **Primary research**
  - Interviews with industry and domain experts to identify constraints, trends and uncertainties
- **Secondary research**
  - Literature search for quantitative values for each identified constraint, trend and uncertainty
- **Model building**
  - Mathematical model construction
  - Data analysis to quantitatively identify the relative importance of each force

Fundamental multiple regression analysis...

Estimate the predicted outcome

Based on multiple quantitative causal factors

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \ldots \hat{\beta}_N x_N$$

Using minimum mean squared error fit

Sometimes, transforms are needed...

$$\log\left(\hat{Y}\right) = \hat{\beta}_0 + \hat{\beta}_1 \frac{1}{x_1} + \hat{\beta}_2 x_2^2 + \ldots \hat{\beta}_N e^{x_N}$$

* Coefficient of determination (R^2) measures how much each causal element explains the estimated outcome

* Correlation coefficient measures how the causal elements are related

Example quantitative model…

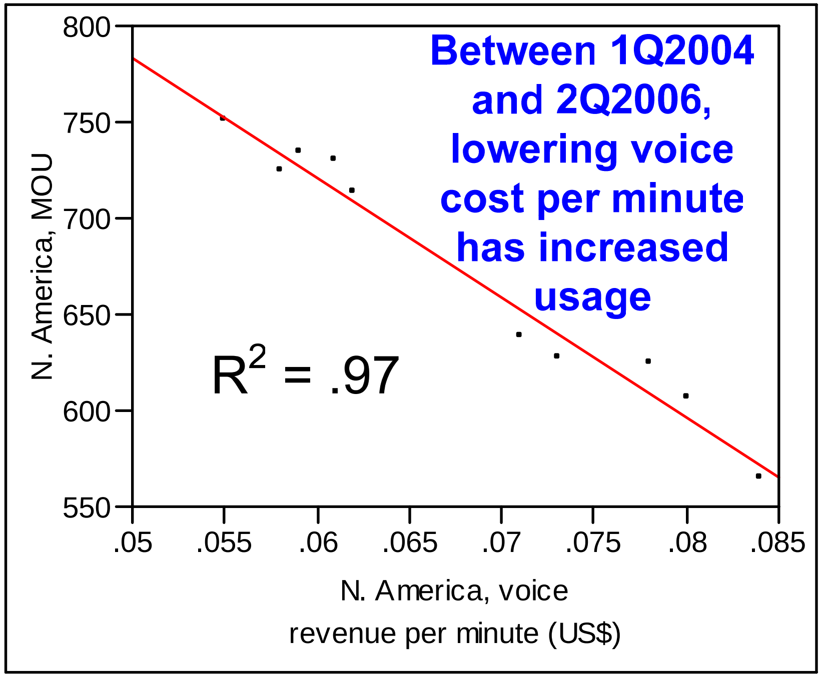
Radio spectrum availability - constraint to wireless revenue growth

N. American voice minutes of usage per month

N. American voice revenue per minute (US$)

$$\hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 x_1 = 1097 - 6266x$$

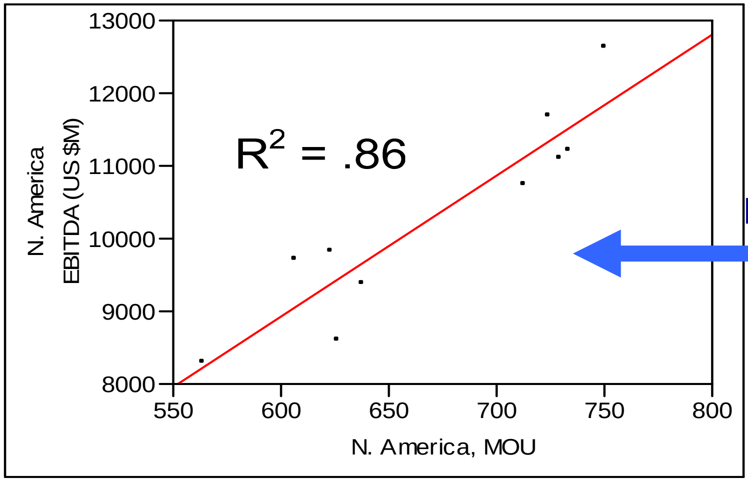
- **North American wireless network operators force monthly minutes of voice usage up by lowering prices**



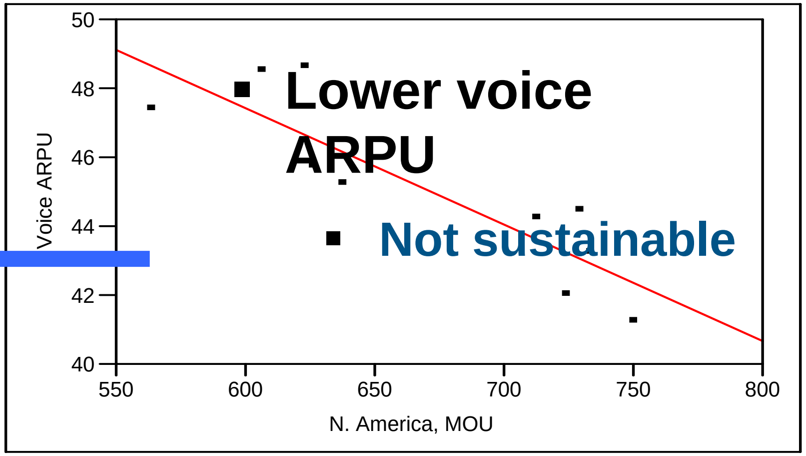
Lower prices = more voice minutes consumed

What happens to profits?

They go up… for now

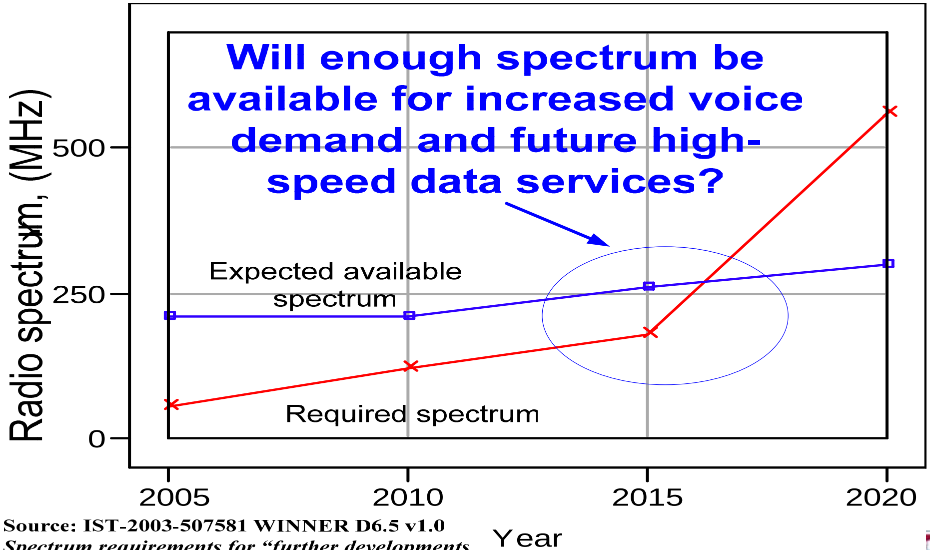


Non causal!



	\$/minute	MOU	EBITDA (\$M)
Starting value	0.085	550	8400
Ending value	0.05	770	12600
Difference	-0.035	220	4200
Change (%)	-41.18%	40.00%	50.00%

- **Lowering prices**
  - **Raises voice MOU**
  - **Decreases ARPU**



Source: IST-2003-507581 WINNER D6.5 v1.0
Spectrum requirements for "further developments of IMT-2000 and systems beyond IMT-2000"

Forces for wireless

These are among those having the highest leverage…

Social

- User expectations
- Information security
- Emergency services

Technological

- Increasing need for spectrum
- Battery life of portable devices
- User mobility

Political

- Spectrum regulation
- Licensing regulation

Economic

- Switching costs
- Consequences of long-term asset acquisition
- Intellectual property costs

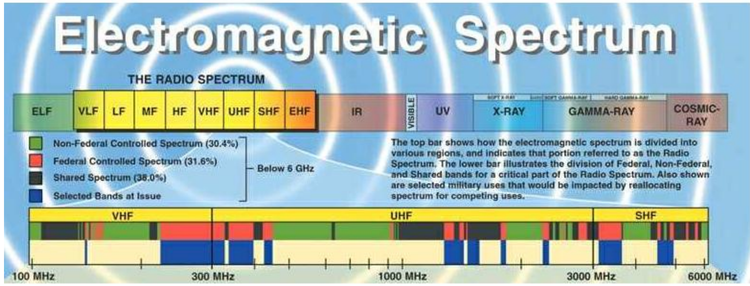
Environmental

- Manufacturing
- Battery and equipment disposal

Technological forces

The laws of physics rule

- **Spectrum availability**
  - The highway on which wireless signals travel
  - Without radio spectrum, the industry could not exist – and we cannot create more
  - Notion of appropriateness for cellular spectrum - 700 MHz to about 3.5 GHz
  - “Spectrum pollution” in unlicensed services already apparent in some areas of high population density



- **Battery life**

  - Mobile devices are portable by nature
  - Growing processing capabilities and application demands are in conflict with the slow development of battery technology

- **User mobility**
  - Greatest strength and weakness
  - The primary problem with mobile communication is that users are mobile – and uncontrolled
  - Trade-off between mobile user experience and practicality of implementation

Sociological forces

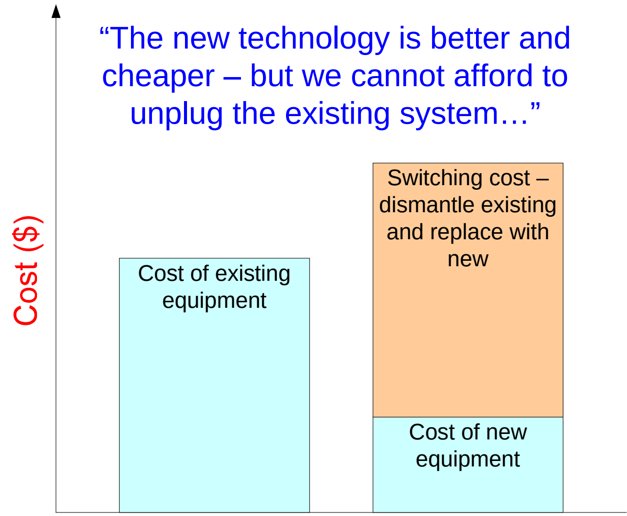
Simple to identify, difficult to quantify, extremely powerful

- **Users' expectations**
  - We have a generation that now takes wireless access for granted
  - Users expect a certain minimum level of service now
- **Privacy & Security**
  - Technology makes it easy to intrude on privacy, location tracking of individuals
  - Fear that the Internet may degenerate into a cesspool of illegal activities, denial of service attacks, highly variable availability – question of whether eCommerce be worth the trouble in the future
  - Paradoxical: - lots of fear but few real breakthroughs
- **Emergency services**
  - Disaster response – legislation by countries to support emergency notification.

Economic forces

Often why the best technical solutions are not adopted

- **Switching costs – difficult to unplug**
  - Very large embedded base of existing networks
  - High fixed cost, low marginal cost – recipe for price war
  - Difficult to break out of equilibrium



- **Asset efficiency**
  - Capitalized assets show up on a company's balance sheet for the public, investors and analysts to scrutinize
  - Reduces key ratios used by analysts
  - Players think twice about their equipment investments

- **Intellectual property rights (IPR)**
  - Operators and manufacturers may not be able to earn economic profits using certain technologies due to excessive demands by patent trolls
  - Economics of industry may not support the royalty structure requested by IPR holders

Environmental forces

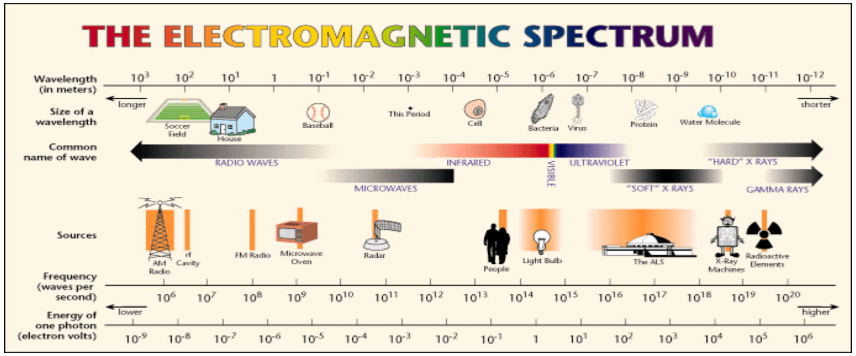
Impact to future generations

- **Humans have always impacted their environment**
  - But today, there are a lot more of us with a lot more impact

- **Disposal of substances**
  - Batteries
  - Displays
  - Chemicals used in manufacturing
  - Plastics
  - Heavy metals used in semiconductors

Political forces

Extremely complex at the global level

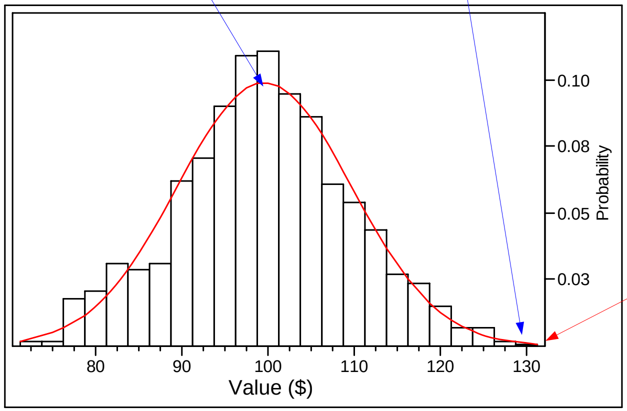


- **Spectrum regulation**
  - Spectrum is a scarce resource
  - Re-farming of spectrum means vacating existing users – where do they go?
  - Who pays incumbents to move?
  - Will there by economic benefit in the end?
  - Economies of scope exist when multiple countries share the same frequencies for the same services – can we all agree on way forward?
- **Licensing regulation**
  - Should a license anticipate a particular technology?
  - Auctions lead to the "winner's curse" – may place unnecessary burden on industry participants, effectively removing certain options

Asset is most likely worth this much...

But the highest bidder wins the auction

The probability that the asset's value corresponds to the winning bid is well under 1%



The winner's curse in an English auction

Forces summary
Mining the edges of the future

- We may not have direct access to future requirements
- But, by looking to the constraints on the industry today, we have a window into what is likely to be valuable tomorrow

Introduction to wireless standards

An insider's view…

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Why standardize?

Global standards are a double-edged sword

- **Geographical and inter/system interoperability**
  - The first systems were proprietary, e.g. a Motorola radio only talked to another Motorola radio and only in areas in which Motorola base stations and infrastructures existed
  - Very small market a serious consequence for proprietary tech
  - Single-source suppler with large monopoly power
- **Economies of scale**
  - Standard technology enables large scale adoption, which fuels the learning curve
- **Economies of scope**
  - Re-use of platform for multiple products – no need for special country-specific technologies
- Standards create large-scale adoption potential
  - For example 3GPP technologies (GSM/GPRS/EDGE/UMTS) now have 82% of the global market share
- A double-edged sword
  - Give up proprietary advantages on one hand, in exchange for the possibility to create large global markets
  - On the other hand, innovation space is constricted to contain technology switching costs – the price you pay for large market creation
  - Wireless is a huge industry
    - In 2005, $468 Bn U.S. in global operator revenue
    - In 2005, $62 Bn U.S. in operator simple free cash-flow

Take 3GPP standardized technologies for example
82% of the global wireless market in 2006

- Source: 3G Americas, 2006

Should your company participate or not?

Non-participation in standards produces severe consequences

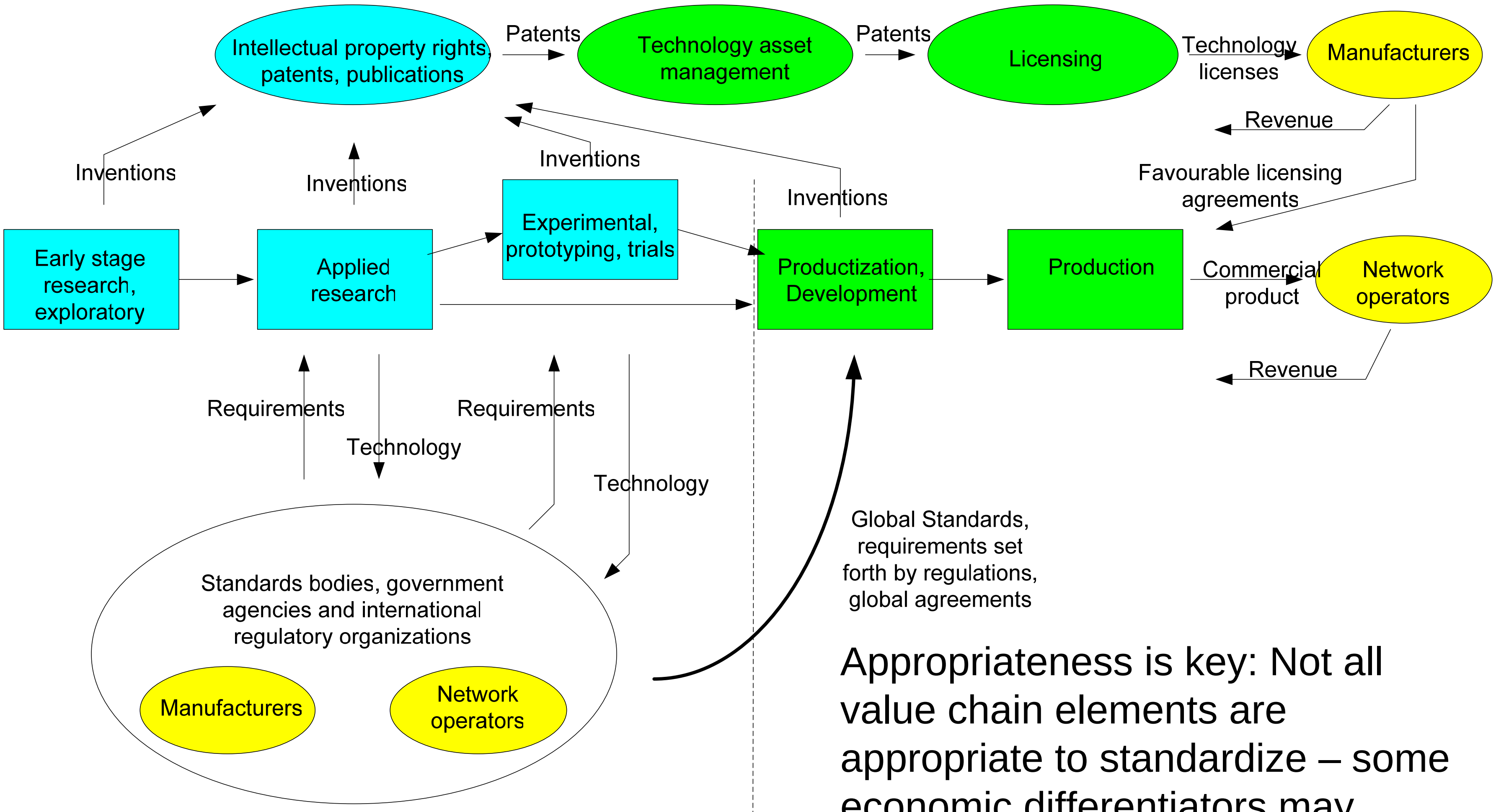
- **“Question: Because the standards process is expensive and time consuming, why don’t we let other companies standardize the technology, and then simply implement the standard after it is published?”**

1. If your company does not participate in the development of standards, then your competitors will write your product requirements for you – and they won’t make it easy given your existing architecture

2. If you did not help develop the technology, then you will pay the contributors to the standard for royalties on their technology

3. Blind implementation of a standard is almost impossible. Standardization is a mutual learning process - if your people did not develop competencies during standardization, you will almost certainly be late to market

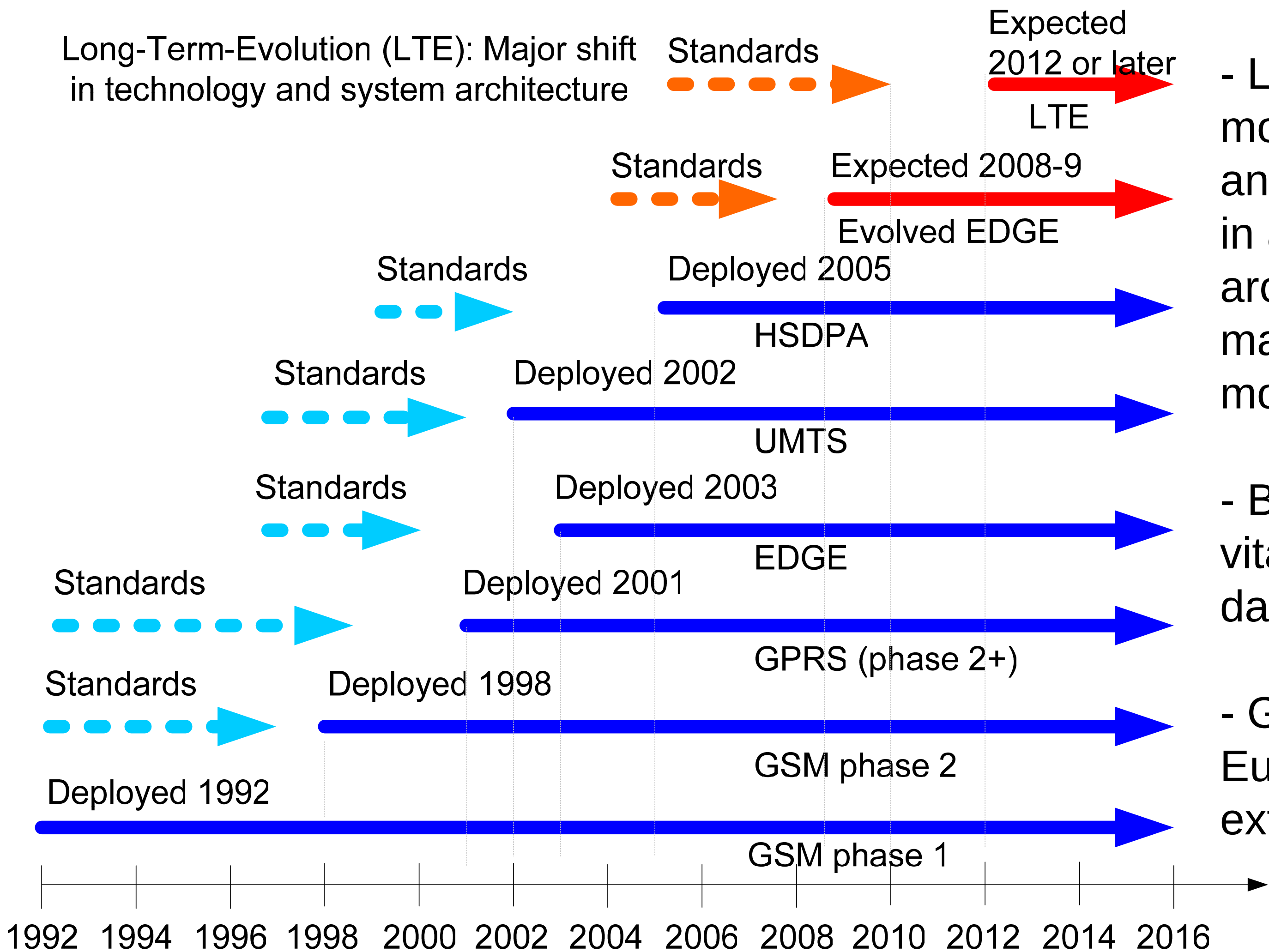
Relationship to the wireless manufacturer's value chain
Many ways to create value



Appropriateness is key: Not all value chain elements are appropriate to standardize – some economic differentiators may remain proprietary

Industry roadmap – major phases

3GPP wireless technologies



- LTE expected to require more time to standardize and deploy – radical shift in air interface, system architecture and management of user mobility

- Backward compatibility: vital 3GPP principle from day one of GSM phase 2

- GSM licenses in Europe have been extended to 2018 - 2024

How are standards bodies created?
Mutual economic benefit is key

- Industry consortia – Companies having complementary (or even competing) interests come together for industrial research collaboration
  - If sufficient interest exists, then a standards body may be formed
  - Pre-standards, long-term visionary bodies, e.g. Wireless World Research Forum (WWRF)

- Standards bodies – Research cooperative groups created for the purpose of developing and maintaining standards
  - Primary bodies for wireless:
    - European Telecommunication Standards Institute (ETSI)
    - 3rd Generation Partnership Project (3GPP)
    - 3rd Generation Partnership Project 2 (3GPP2)
    - Institute for Electrical and Electronic Engineers (IEEE)
    - Open Mobile Alliance (OMA)
    - International Telecommunications Union (ITU)

How are standards themselves created?

Example: 3rd Generation Partnership Project (3GPP)

- Someone proposes a Work Item Description (WID)
  - For example: Advanced receivers, GPRS, EDGE, HSDPA, RX Diversity, etc… any feature to a system – or an entire system
  - A rapporteur is assigned – edits the output docs, convenes ad-hoc meetings
- Companies meet in ad-hoc meetings (over 1 year+)
  - Bring in proposed solutions
  - Simulation results
  - Liaison statements are written to, and received from other working groups regarding any impacts among working groups
  - Agree on general direction – output technical report (TR)

After companies agree on principles…

The actual standards drafting begins

- Core specifications are drafted
  - Requirements and technical specifications are agreed upon and written into core specifications
    - Stage 1 – Service Description
    - Stage 2 – General architecture and requirements
    - Stage 3 – Detailed implementation requirements
- Test specification work begins
  - Test specifications are intended to enforce the requirements of the core specifications
  - Number of test spec CR’s biggest predictor to adoption

Standards drafts are subject to oversight

The standards bodies must agree and approve all drafts

- Contributions are agreed by working groups
  - For example, in TSG GERAN
    - Radio physical layer is handled by WG1
    - Signalling is handled by WG2
    - Testing is handled by WG3
- Specification is approved by plenary
  - Agreed specifications are sent to plenary for final approval
  - Version number assigned
  - Specification placed in public directory area for access

If you ever need to work in a standards body…

Ongoing credibility and flexibility are key

- A new document or idea is NEVER sent to a meeting with a delegate or researcher, unless it has been sent out to the Working Group (WG) email list for comments, corrections, etc.
  - Surprises involving major shifts in general direction are not appreciated and may raise suspicion about a company's motives
- Delegates should avoid the use of slang and/or idioms – the official language of 3GPP is English, but most members do not have English as a first language
  - This may seem obvious, but we still see slang creeping into specifications at times and implementers with questions as to what these terms mean
- Everything you say in the meeting may be entered into the minutes and made public
  - Be cautious to avoid disclosing trade secrets
- Identify errors quickly
  - If you bring documents, simulation results, etc. with major errors into a standards body, please inform the group of the errors as soon as you discover them
- ETSI/3GPP are consensus driven
  - Failure to agree is viewed very negatively
  - Technically, there can be a vote, but there has yet to be such a vote ever in ETSI over a technical disagreement. (only votes for officers)
  - A vote on a technical issue is considered shameful in ETSI/3GPP and may cause difficult-to-repair reputation problems for offending companies.
- Take time to learn the business culture and procedures of the participants
  - European, U.S., Canadian, Chinese, Japanese, Indian, etc. all have differences in working culture
- Learn how the standards body operates at a procedural level
  - Find a mentor
- Identify the key players and reach out to as many as possible
  - There are not that many
  - Keep doors open at the executive, researcher and delegate levels

The technologies

Addressing the forces over the next 10 years…

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Important technologies for next-gen wireless

How will the industry address these forces going forward?

Wireless System Architecture

- Trend toward flat architecture
- More flexible mobility control

Information Theoretic Advances

- Modulation/equalization
- Advanced receivers

Cross-Layer Design

- End-to-end customization
- Transcoding, E2E QoS control

Dependencies

Cognitive and Flexible Radio

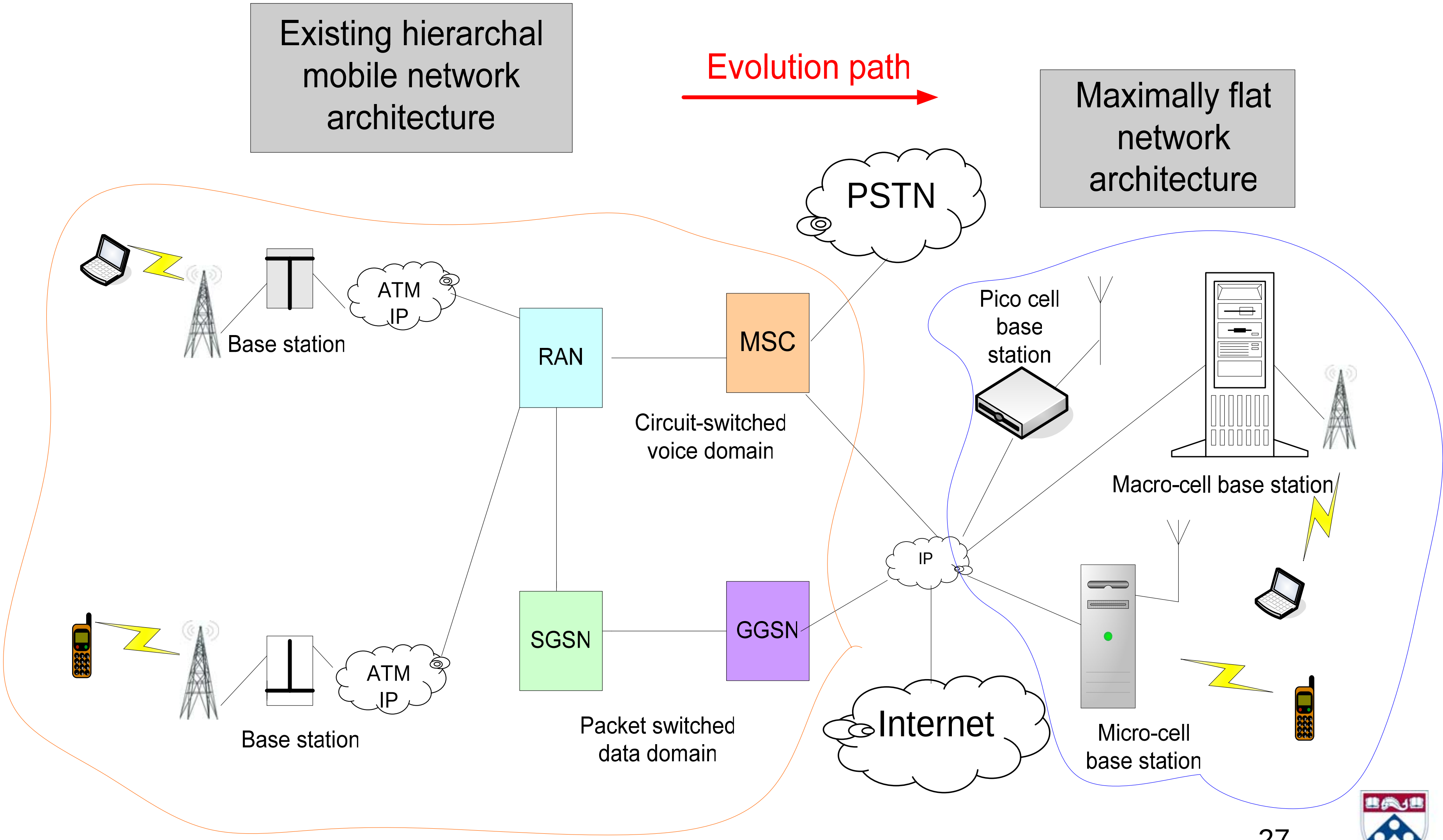
- Transform Domain systems
- Enabling spectrum sharing

Antenna Technology

- Smart antennas, MIMO
- Multi-band antennas

System architecture for next-generation wireless

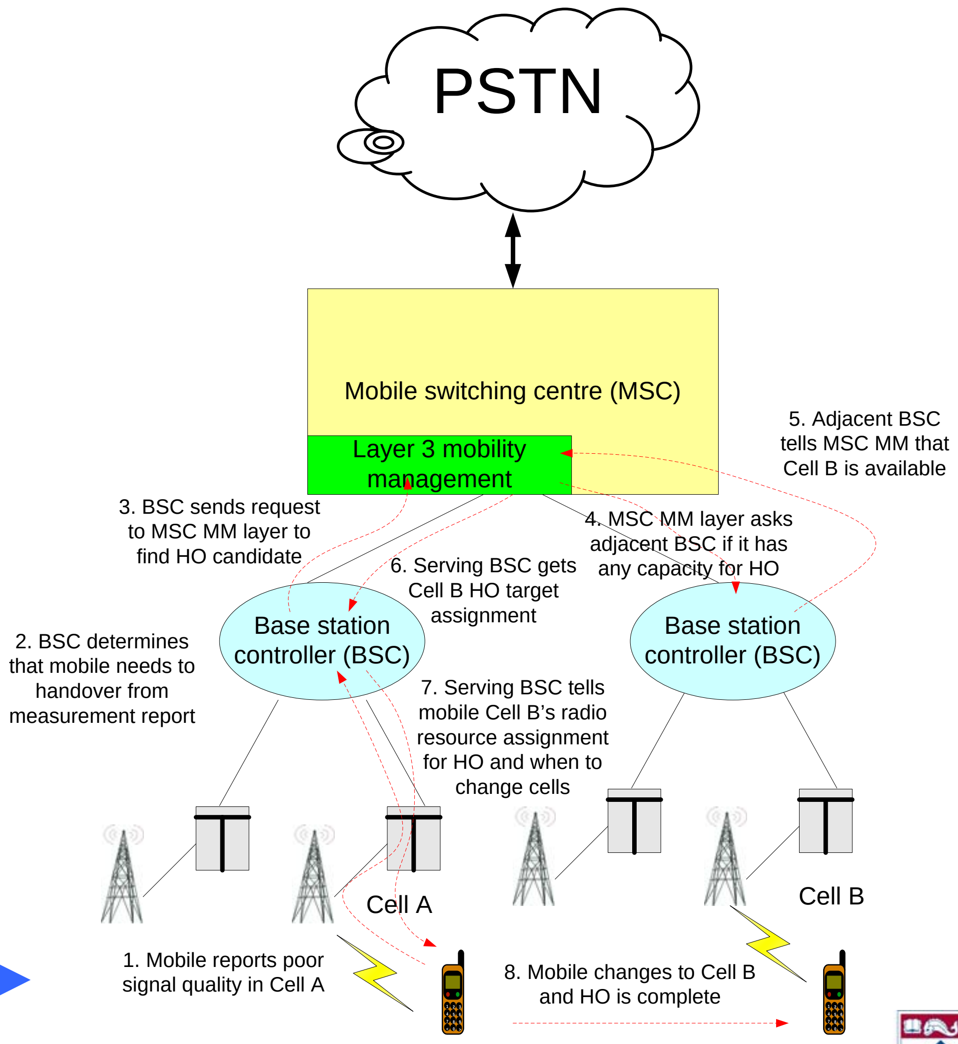
Industry trend toward maximally flat architectures



Why does mobile network architecture matter?

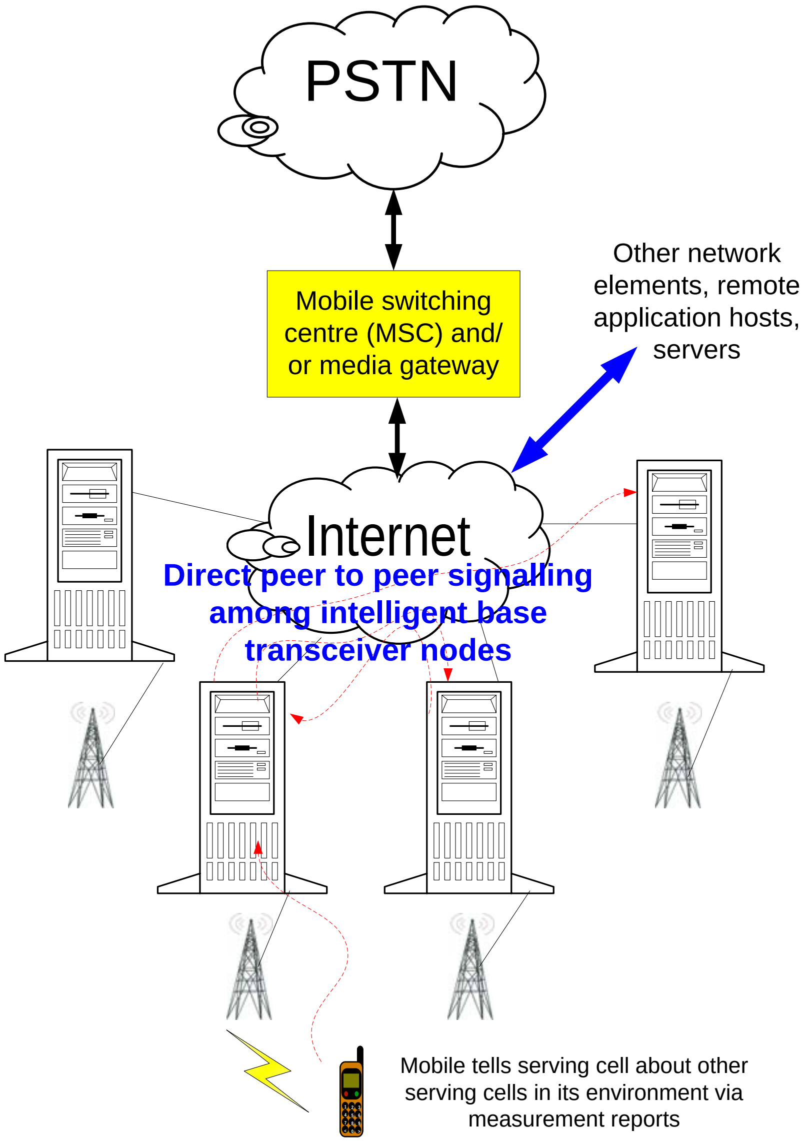
Contrast mobility management, latency, QoS control

- When the existing network architecture was developed, hierarchal architecture was needed
  - Intelligence needed to be more centralized
  - It was too costly and consumed too much space to put large amounts of intelligent control very near to the radio interface
- Latencies are key to architectural consequences
  - Latencies highly variable and difficult to control
  - Mobility management cumbersome and uncertain due to high latencies
  - Much more signalling traffic on both the backhaul and radio interface than ideal
- Consider the dynamics of a circuit-switched voice call handover from Cell A to Cell B



Flatter architecture is much more responsive

Distributed intelligence – close to the radio layer

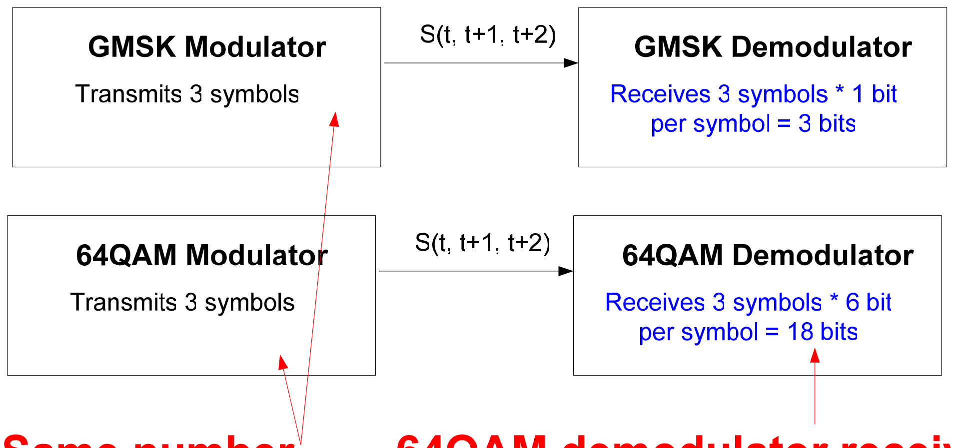


- Maximally flat architecture puts intelligence near the radio layer
  - Quick and responsive mobility management control
  - Shorter latencies for data traffic
  - Greater control over fewer bottlenecks
  - Rapid Quality of Service (QoS) management
  - Minimal use of physically distant intermediaries whenever possible

Information Theoretic Advances

Modulation techniques, equalization, advanced receivers

Look for higher-order modulation techniques in the coming years



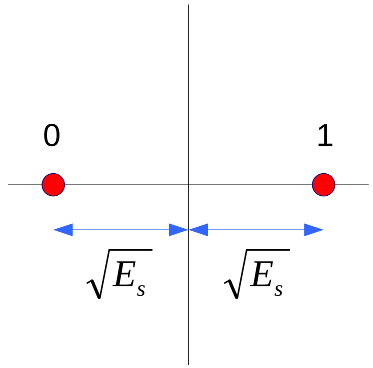
Same number of symbols transmitted

64QAM demodulator receives 6 times the number of bits received by the GMSK system

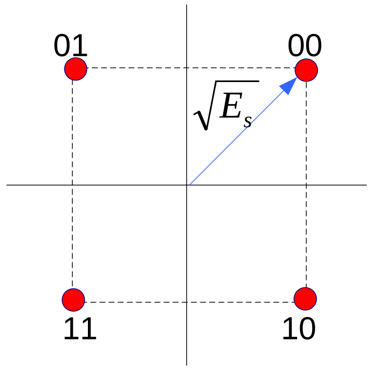
- **Why?**
  - More processing power available every year
  - Steady improvements in equalizer technology
- **More bits per symbol**
  - More information available per symbol transmitted means…
  - Faster data rates
  - Greater system capacity
  - Take advantage of local signal quality maxima

Evolution of modulation techniques

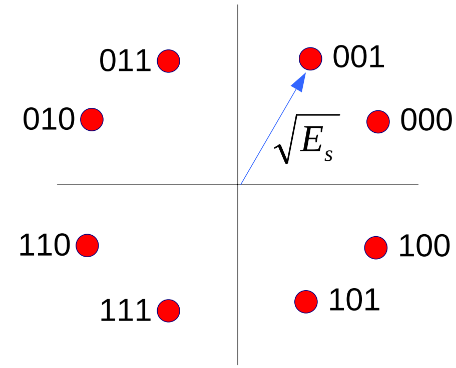
More bits per symbol – more throughput, higher capacity



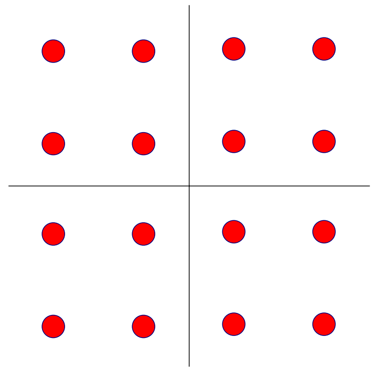
Bi-phase modulation:
1 bit/symbol



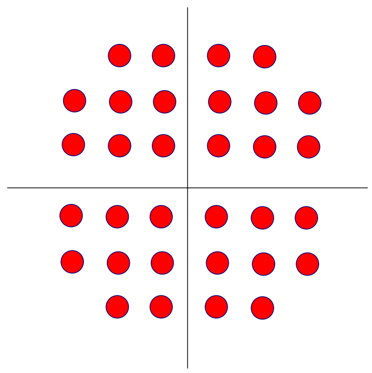
Quadrature phase shift keying (QPSK): 2 bits/symbol



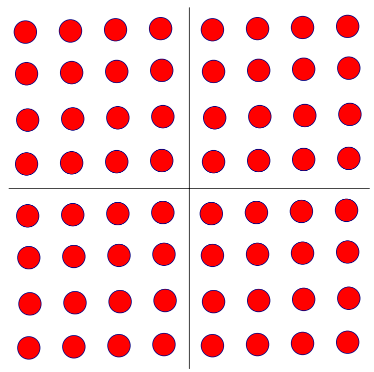
8-level phase shift keying (8PSK): 3 bits/symbol



16 Quadrature amplitude modulation (16QAM) modulation:
4 bits/symbol



32 Quadrature amplitude modulation (32QAM) modulation:
5 bits/symbol



64 Quadrature amplitude modulation (64QAM) modulation:
6 bits/symbol

But we cannot add bits/symbol indefinitely…

No magic – want faster data rates? Need more link margin!

Shannon's Theorem

States that the maximum number of bits/symbol we can support is limited by i) bandwidth and ii) signal quality

Channel capacity, i.e. max number of bits/symbol

$$C = B\log_2\left(1+\frac{S}{N}\right)$$

How much bandwidth do we occupy?

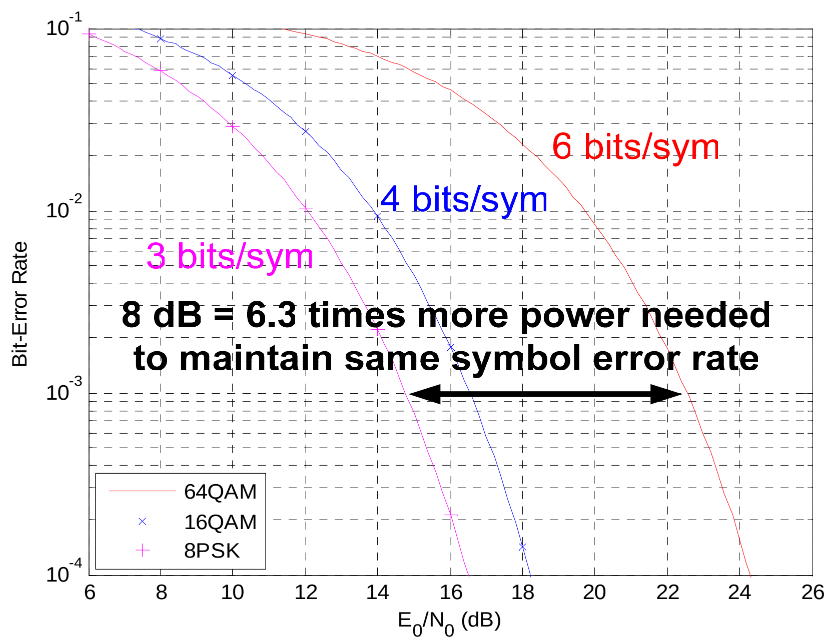
What is the quality of our signal?

C = capacity in bits/symbol
B = Bandwidth occupied by signal (Hz)
S = Signal strength (W)
N = Noise level (W) = kTb = thermal noise floor

Shannon's theorem in action – compute probability of symbol error

$$P_{se}(\eta_s) < erfc\left[\sqrt{\eta_s}\sin\left(\frac{\pi}{M}\right)\right]$$

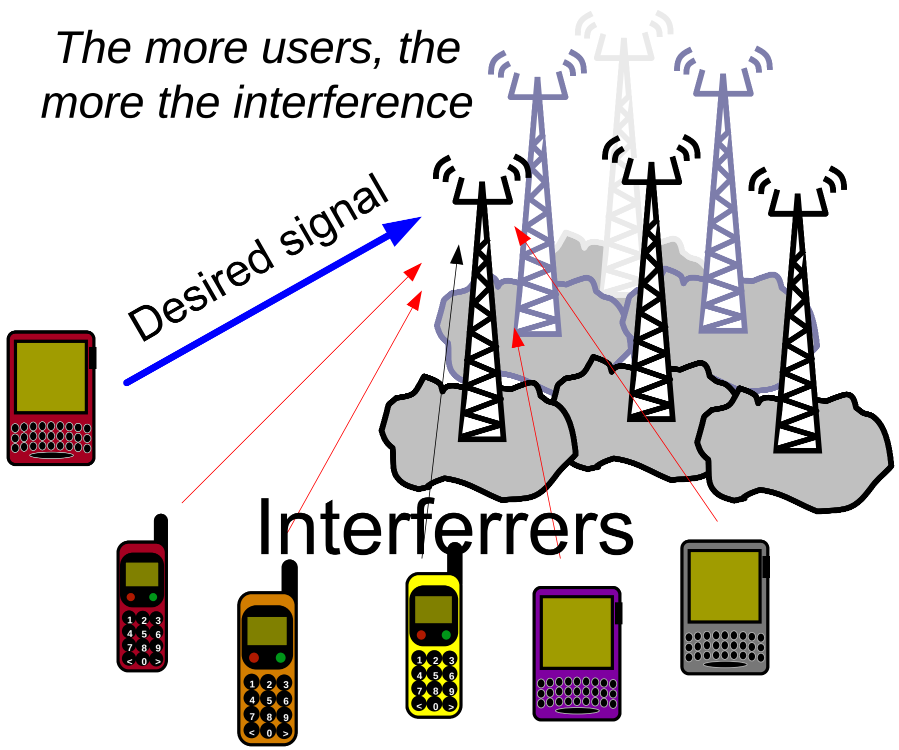
Where $\eta_s = E_s/N_0$ *is the symbol signal-to-noise ratio (SNR),* E_s *is the energy per symbol, and* $N_0/2$ *is the power spectrum density (PSD) of the AWGN.*



Advanced Receivers

Helps approach theoretical limits in the real world

The more users, the more the interference

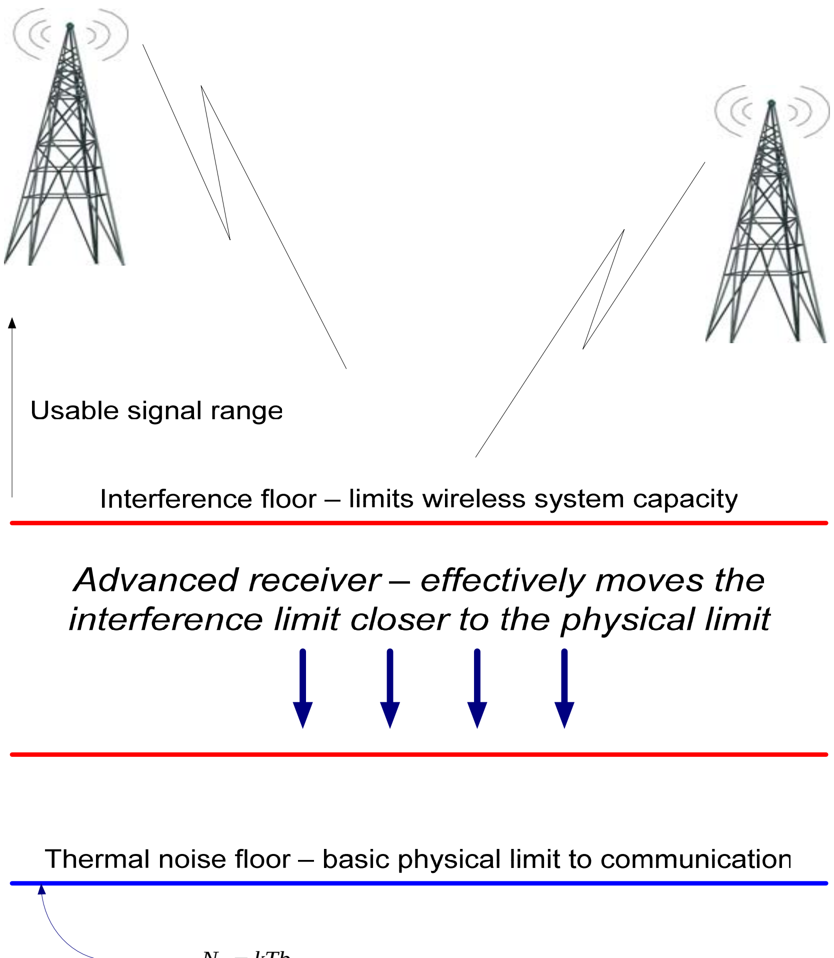


The capacity of wireless cellular systems is interference limited

- System capacity is highly dependent on channel capacity…
- …which is dependent on signal quality, or Carrier to Interference (C/I) ratio
- More users on system = more interference = lower signal quality
- An advanced receiver enables normal reception of signals through large amounts of interference
- Applicable to both base stations and mobile terminals

Greater immunity to interfering signals

Effectively moves the interference floor toward thermal noise



$N_0 = kTb$

$k = 1.38\times10^{-23}$ = Boltzmann's constant

$T = 288K$ = average earth temperature, Kelvin

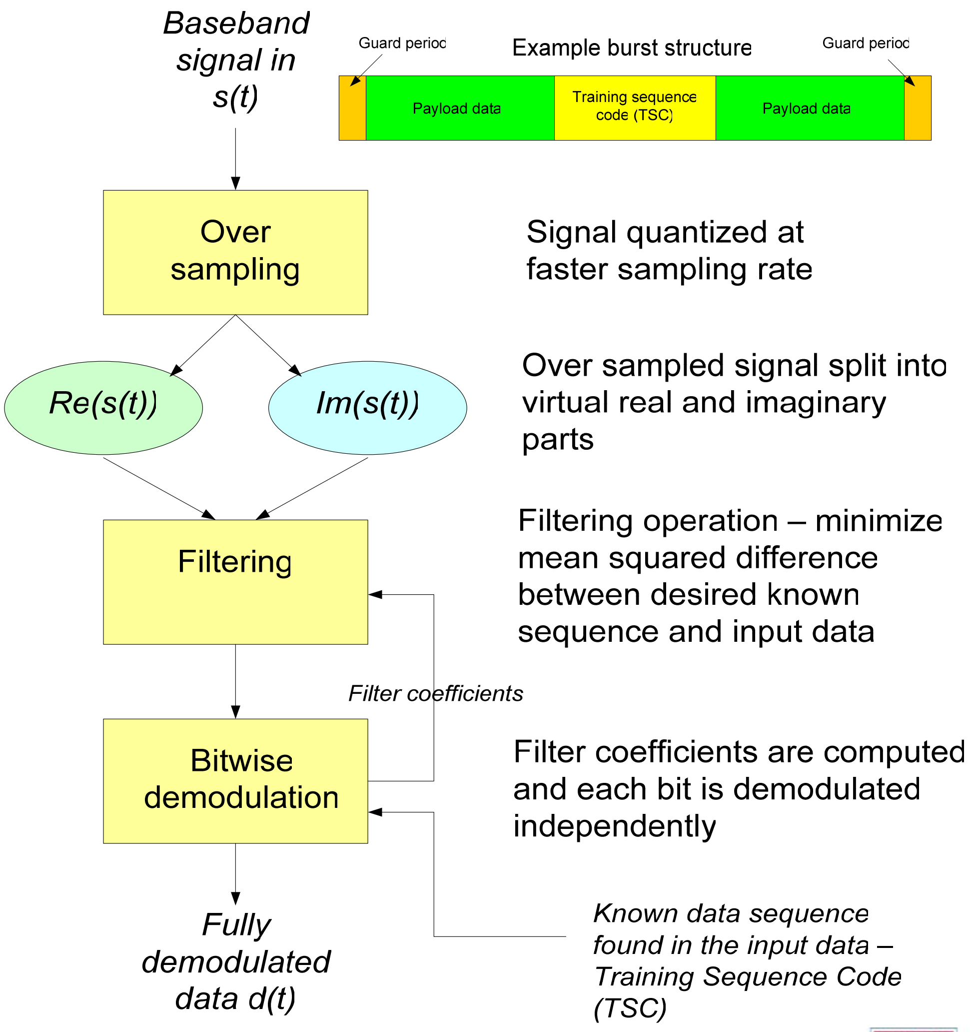
B = Bandwidth, Hz

- Spectrum pollution comprises the rise of interference above the natural physical background of thermal noise
- Advanced receivers allows decoding of information at much higher levels of interference, closer to the basic physical limit than conventional demodulation

Many approaches to advanced receivers

Some are "blind" methods, others need a hint at what to expect

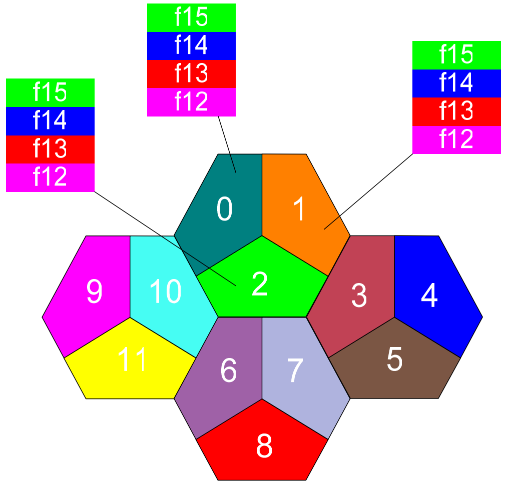
- Several techniques: Weiner filtering, Joint Detection, Joint Space-Time Optimized Filtering and others
- Some techniques make use of known characteristic of desired signal, e.g. Training Sequence Code (TSC) and minimize mean squared error between known TSC and desired signal – minimizes detection error of unknown bits
- Other techniques are blind methods, that do not need *a priori* knowledge of a training sequence



How do advanced receivers increase capacity?

Economic benefit to network operator & better quality to user

- With 1/1 frequency re-use, you can only load the cells on f12 to f15 up to around 25% capacity due to greater co-channel interference
- But with 4 of them you get 100% of a 4/3/12 normal re-use cell, so you have doubled your capacity by adding only 33% more spectrum…
- and an advanced receiver can give you 4 times the capacity with only 33% more spectrum!



BCCH carriers on f1 - f11 are associated with TCH carrier frequencies f12 - N, where N = 15

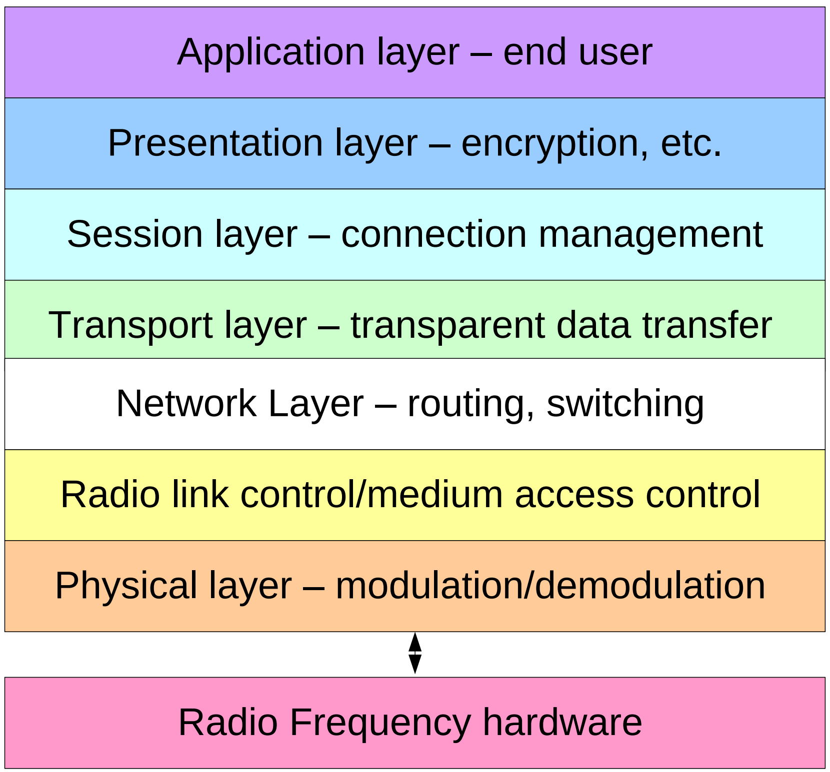
Example of a 4/3 frequency reuse pattern used for BCCH carriers with a 1/1 frequency reuse pattern for TCH carriers.

- BCCH carrier repeated over 12 cells – 2.4 MHz for GSM
- Example: A fractionally loaded system may repeat f11 – f15 on each of the cells
  - 1/1 re-use pattern
  - high co-channel interference

Cross-Layer Design for Wireless

Wireless-aware applications, end-to-end QoS control

Traditional view of layered heierarchy



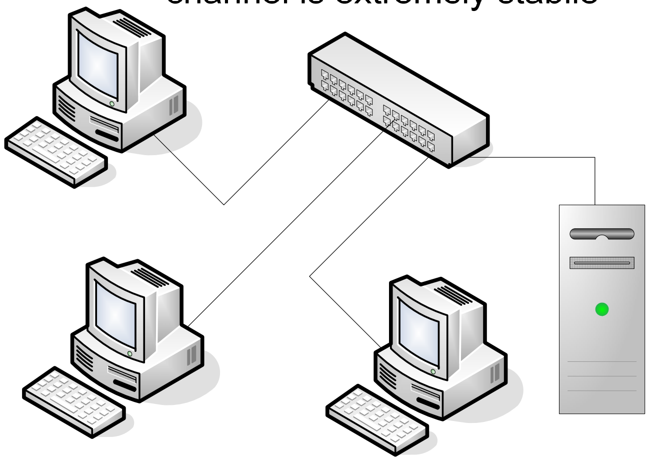
- Layered architecture was adopted in mobile communication as an outgrowth of the wire line world
- Each layer has no knowledge of any other layer's state, parameters or contextual information about data

Wireless vs. wire line transmission channels

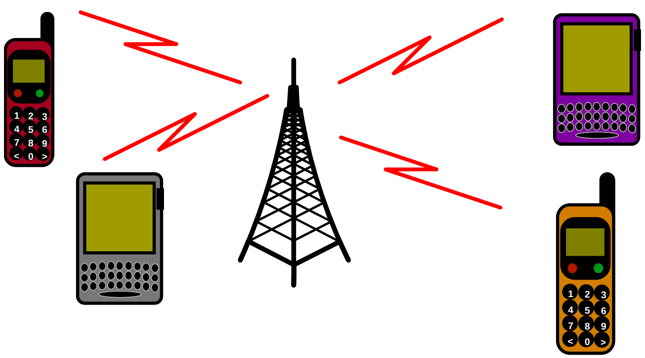
Wireless channels are thousands of times more variable

- Hiding state and contextual information between layers was appropriate and indeed a clean architectural choice in a world in which the physical layer was relatively stable, e.g. in wired communication
- Due to the extreme variability of the wireless fading channel, there are times when “upper layers” may benefit from state information provided by the layers below

The wired transmission channel is extremely stabile



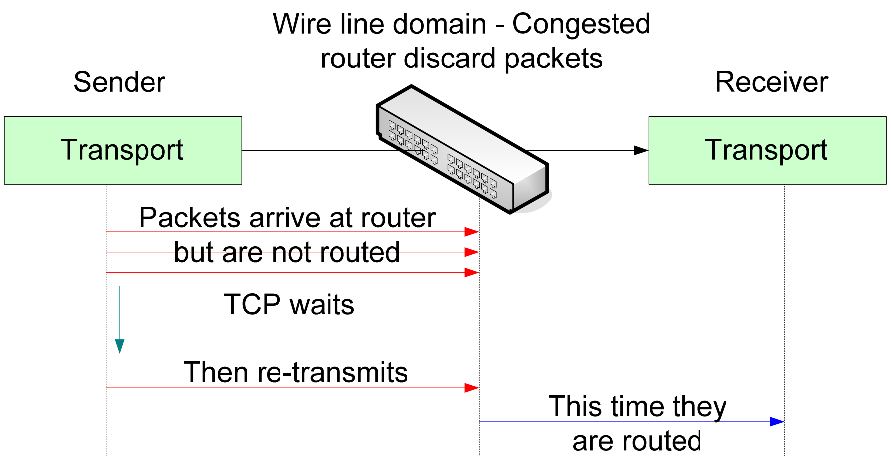
The wireless transmission channel is highly variable

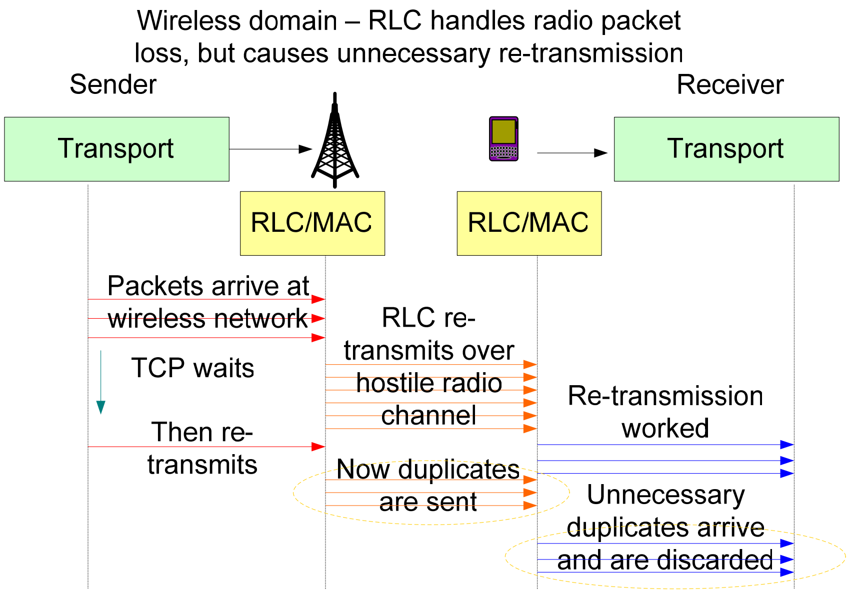


Example inconsistency – wire line/wireless

Transmission control protocol (TCP) – very different behaviour

- In a wired world, TCP knows that if it does not receive an acknowledgement within a certain time, there was likely a bottleneck at a router, which must throw packets away when it cannot handle the load
  - TCP then collapses it transmission window…
  - …and waits a random period before trying to send data again

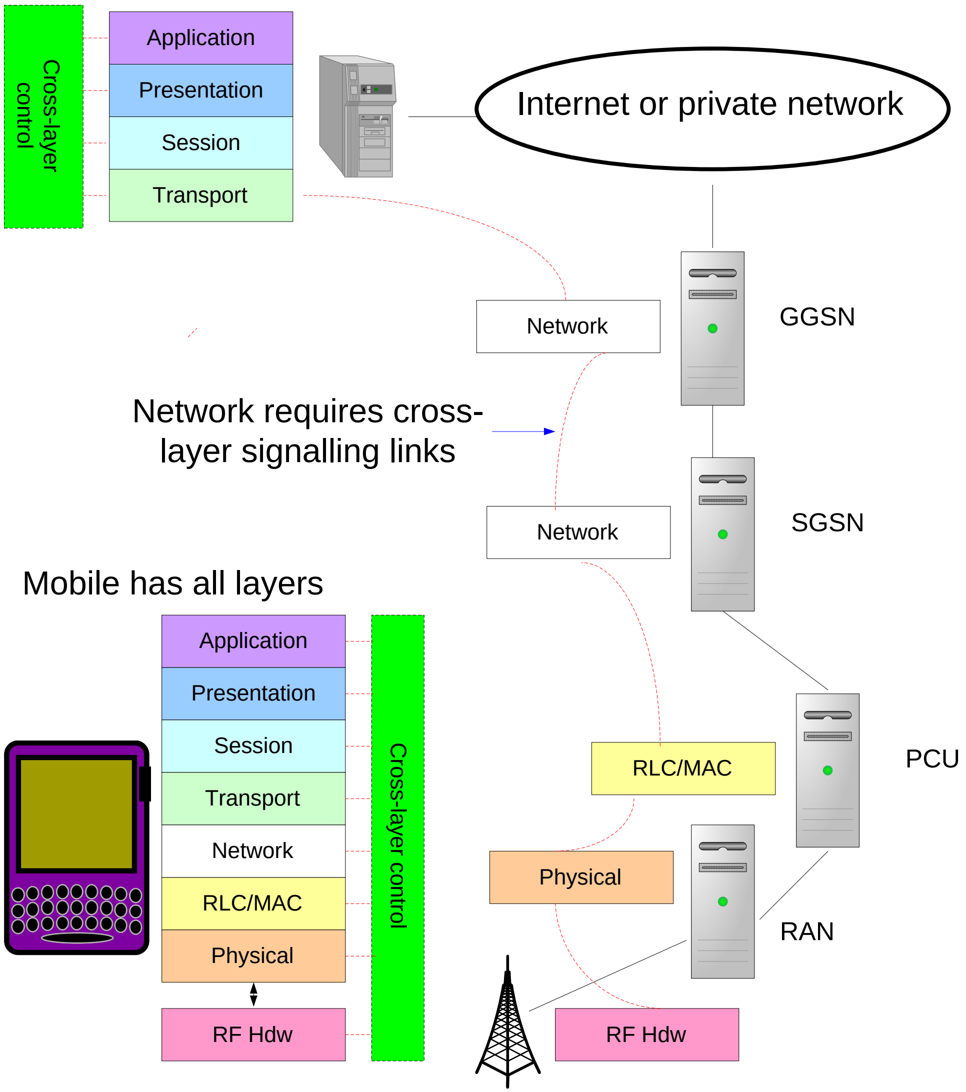




- In a wireless world, lack of a TCP acknowledgement may only mean that the radio link control (RLC) and/or mobility functions are handling a temporary outage condition, but nothing was lost at all
  - Results in TCP collapsing its window size, then re-transmitting data that were already in the radio system anyway, wasting bandwidth with duplicate packets
- This is a case where Transport Layer could benefit from knowing about the radio state

Cross-layer design – inter-layer communication

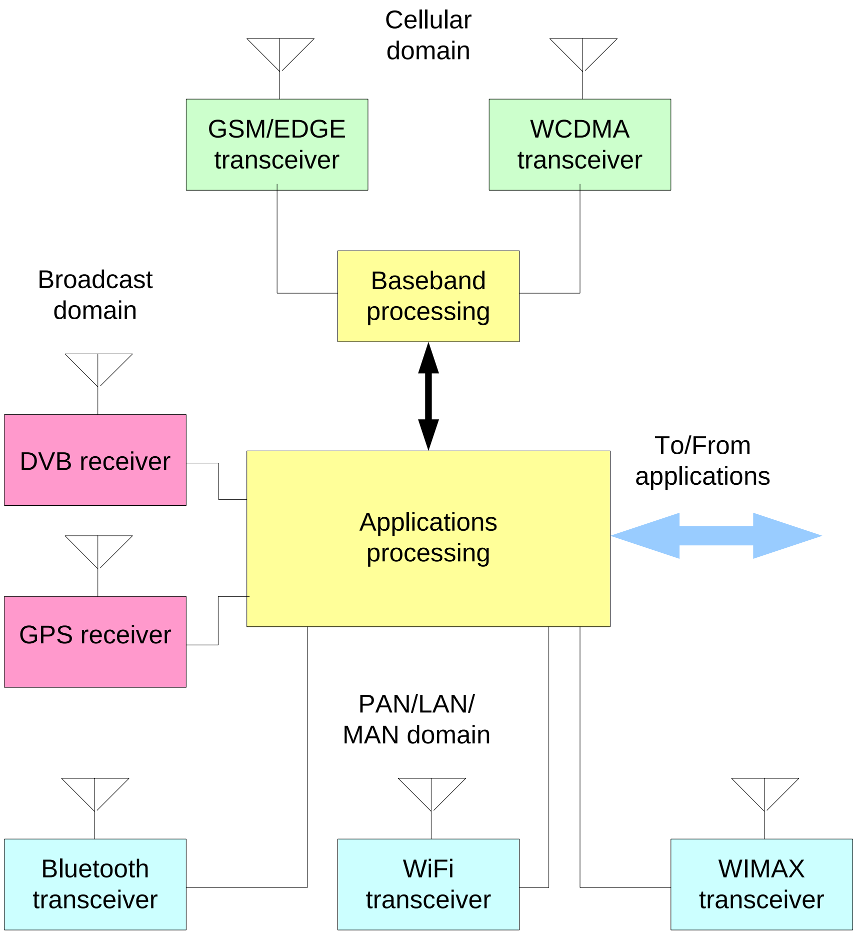
Upper layers may then apply better intelligent control



- Cross-layer design used to be considered a "protocol violation"
- Cross-layer communication is much simpler within the mobile, which supports all layers
- In the network, signalling must be devised , as the layers may not even reside in the same city as one another
- Permits inter-layer optimization and end-to-end Quality-of-Service (QoS) control

Software Defined Radio Systems
Contrast to conventional radio architecture

Conventional architecture



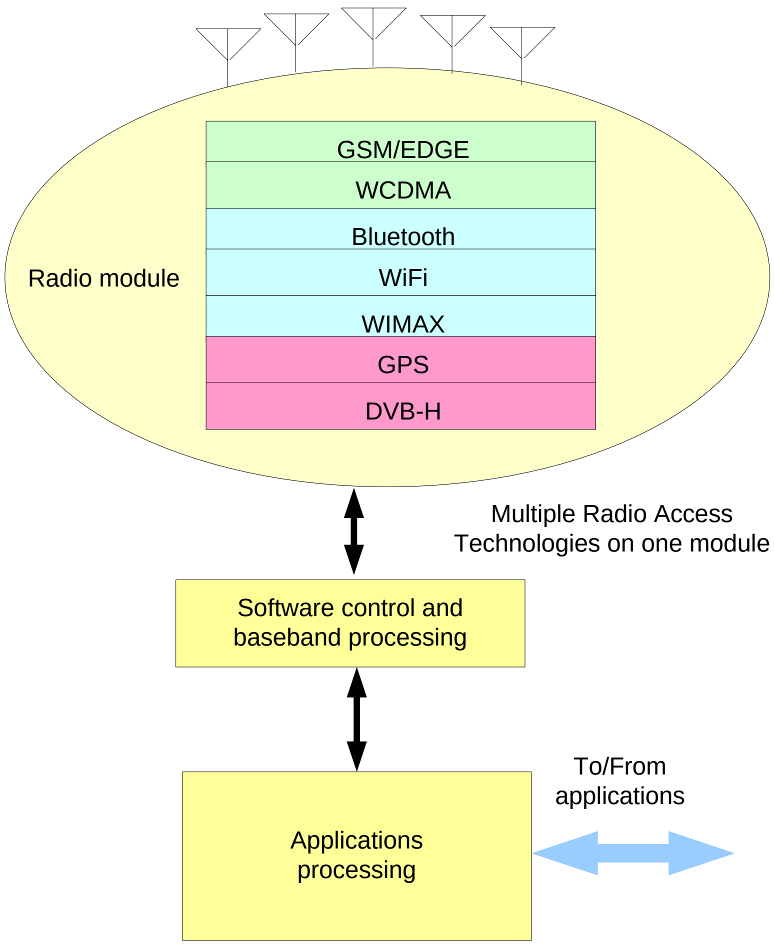
- Conventional radio architecture separates functionality among multiple components
- Each wireless mode must be handled by an entirely separate radio
- As the wireless industry evolves, conventional architecture presents greater challenges
  - Higher parts count
  - Greater physical complexity

Software Defined Radio Systems

More processing, closer to the Radio Frequency layer

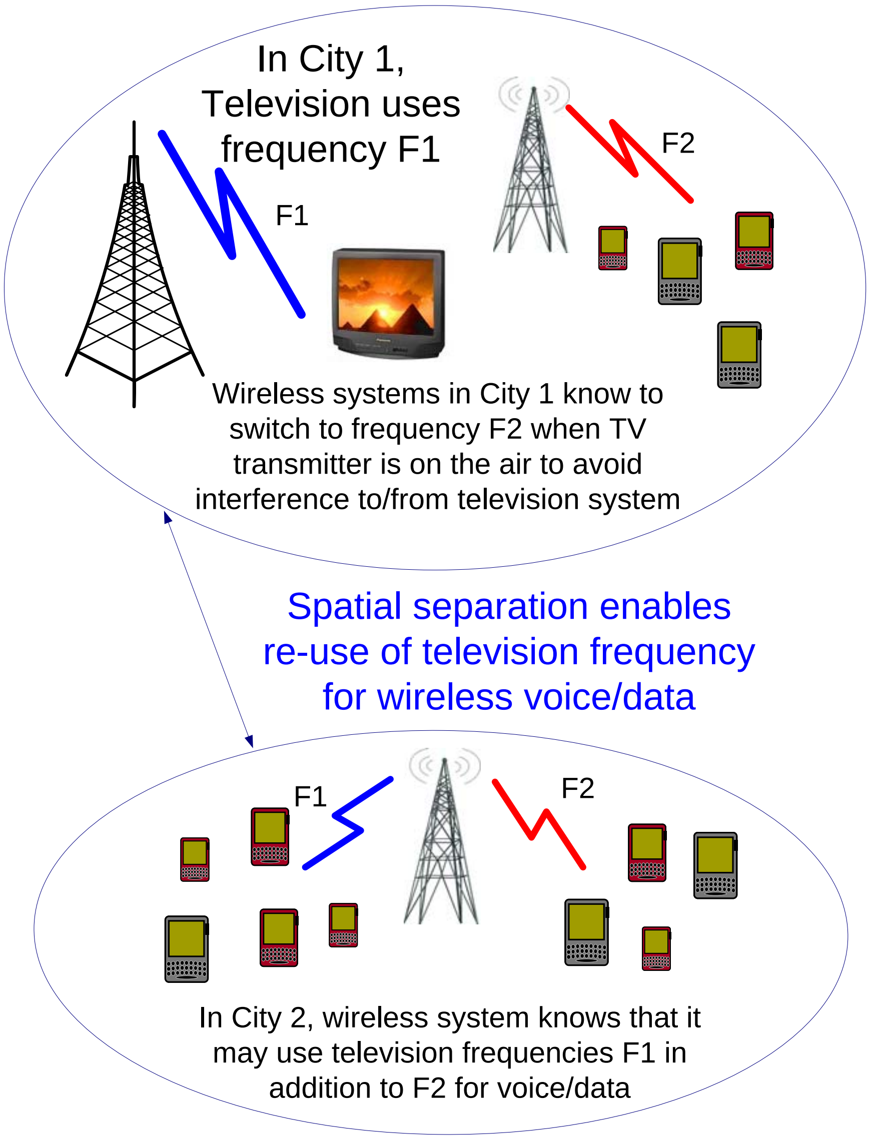
- A Software Defined Radio (SDR) is a Radio
- Frequency (RF) hardware system capable of generating and detecting signals specified by controlling software
- Industry and academia have many definitions for SDR
  - Some view SDR as a flexible radio subsystem in which software controls the selection of a finite set of pre-determined bands and modes
  - The ultimate SDR would be the concept of a "Universal radio frequency Turing machine" that would generate and detect any arbitrary waveform unlimitedly over the entire electromagnetic spectrum
  - The SDR forum specifies degrees of "software definability" that describe flexibility somewhere between these extremes
- Principal SDR characteristic: migration of intelligence closer to the radio hardware
- Fundamental SDR concept: flexibility
  - More frequency bands
  - More operational modes
  - Enables cognitive radio concepts
  - Extreme agility among modes, bands, frequencies

Software defined architecture



Cognitive Radio Systems

Enables spectrum sharing, greater flexibility

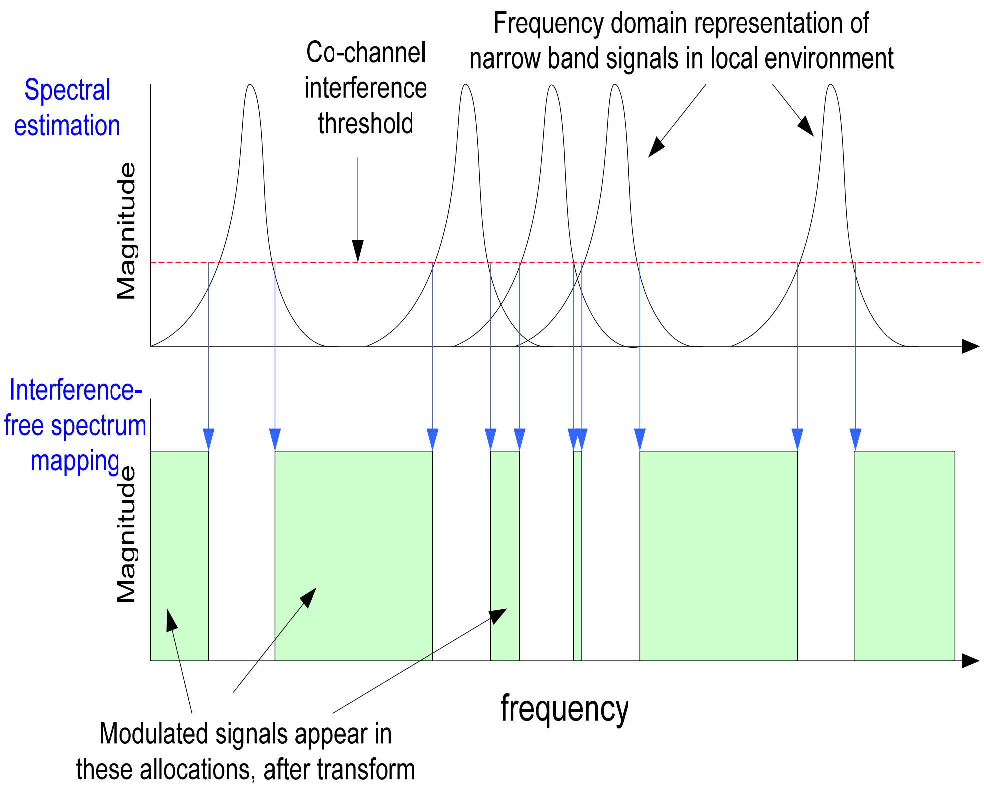


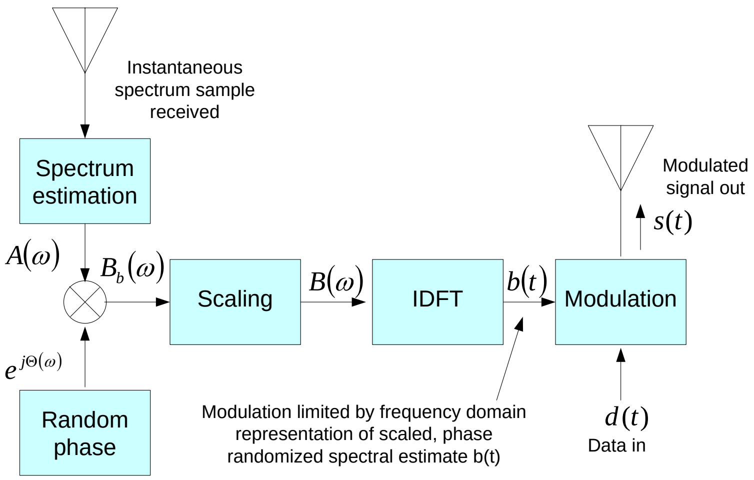
- **Smarter mobile radios**
- **Acquire information about surroundings**
  - **Noise**
  - **Interference**
  - **Channel impairments like delay spread, etc.**
- **Intelligent control of radio subsystem using acquired information**
  - **Avoid interferers – may change frequencies**
  - **Increase tolerance to interference – control advanced receivers**
  - **Adaptation to a certain environment's channel impairments – may switch to different air interface technology**

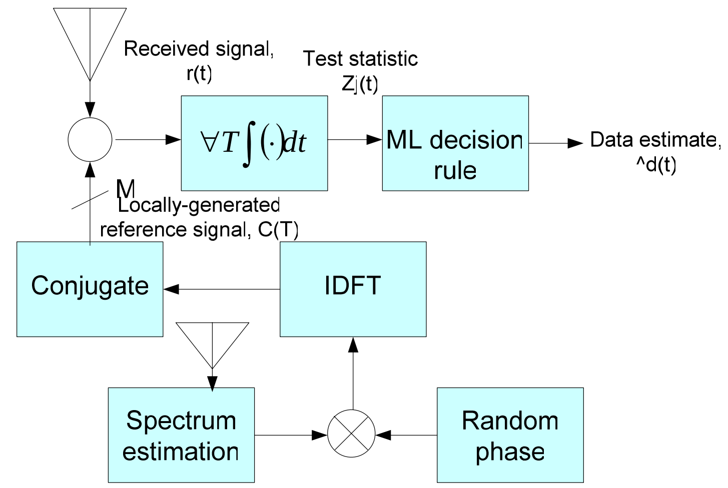
Cognitive and Flexible Radio Systems

Transform domain communication systems (TDCS)

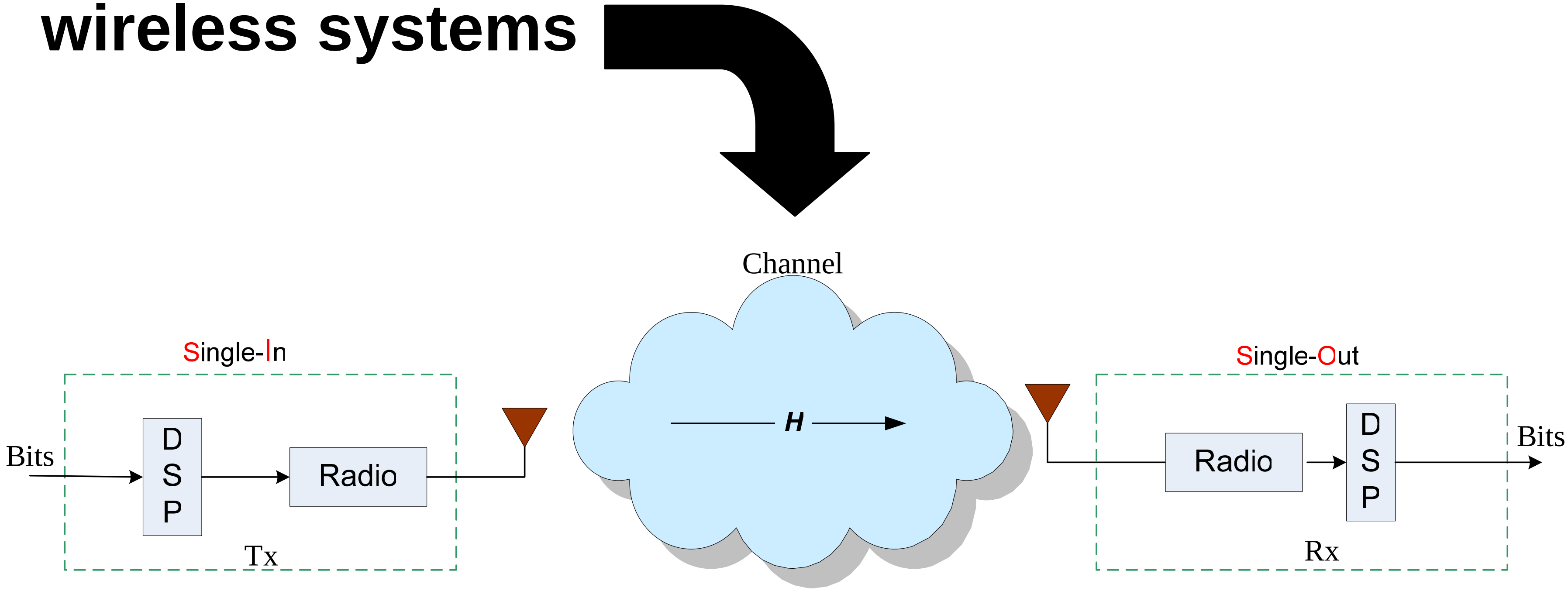
- Extreme frequency agility
- High speed spectrum estimation
- Fit useful information between interference spectra thousands of times each second







Current state of the art for most wireless systems

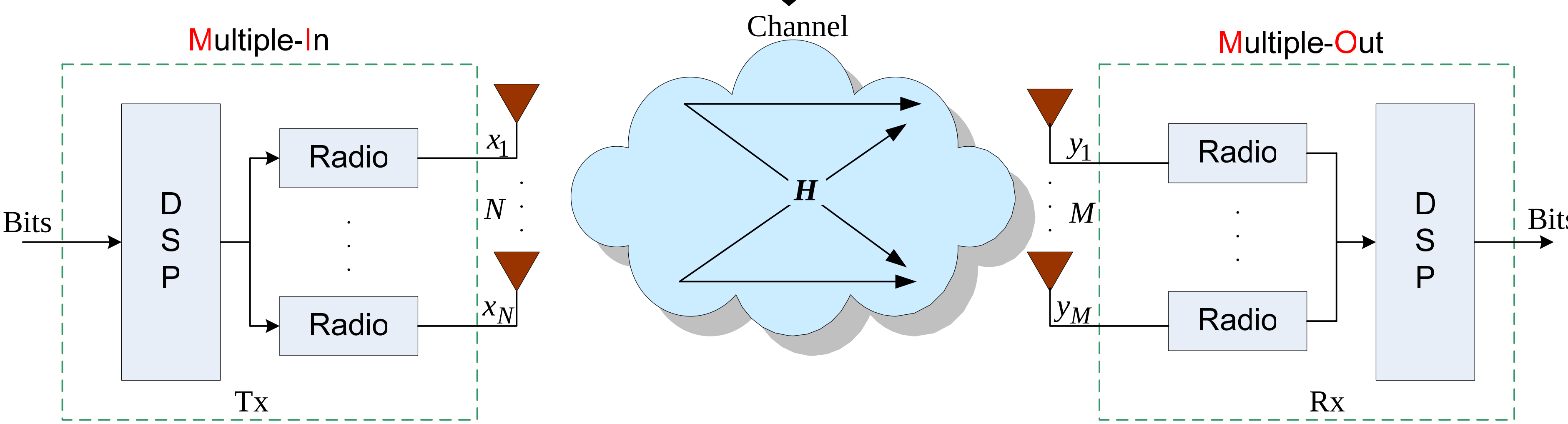


Single antenna on both ends
Single channel transfer function (H)

Multiple Input Multiple Output (MIMO)

Multiple antennas, multiple channel transfer functions

Where the industry is going

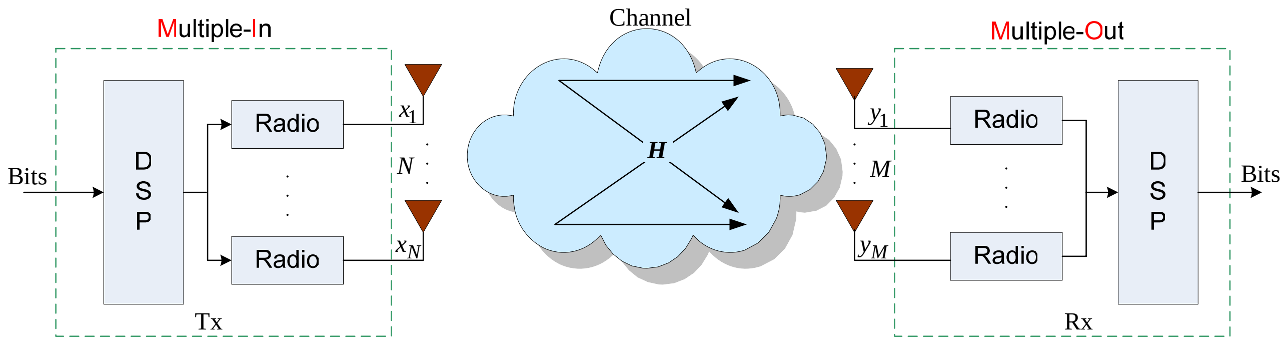


Multiple antennas on both ends

Multiple channel transfer function (H)

Multiple Input Multiple Output (MIMO)

Greater system capacity, better performance



- Symbols are interleaved between transmitters
- Multiple signals are transmitted at the same time and frequency
- A linear combination of the transmitted signals are received

$$\boldsymbol{y}(t) = \boldsymbol{H}(t)\boldsymbol{x}(t) + \boldsymbol{n}(t)$$

- For a full-rank fixed *N*×*M* AWGN channel, the channel capacity is

$$C = \min(N, M)\log_2\left[1 + \frac{\rho}{\min(N, M)}\right] \quad \text{bits/s/Hz}$$

Where: $\rho = \dfrac{E_b}{N_0}$ for the noise-limited case

MIMO and variations

Capacity and performance, but at a price…

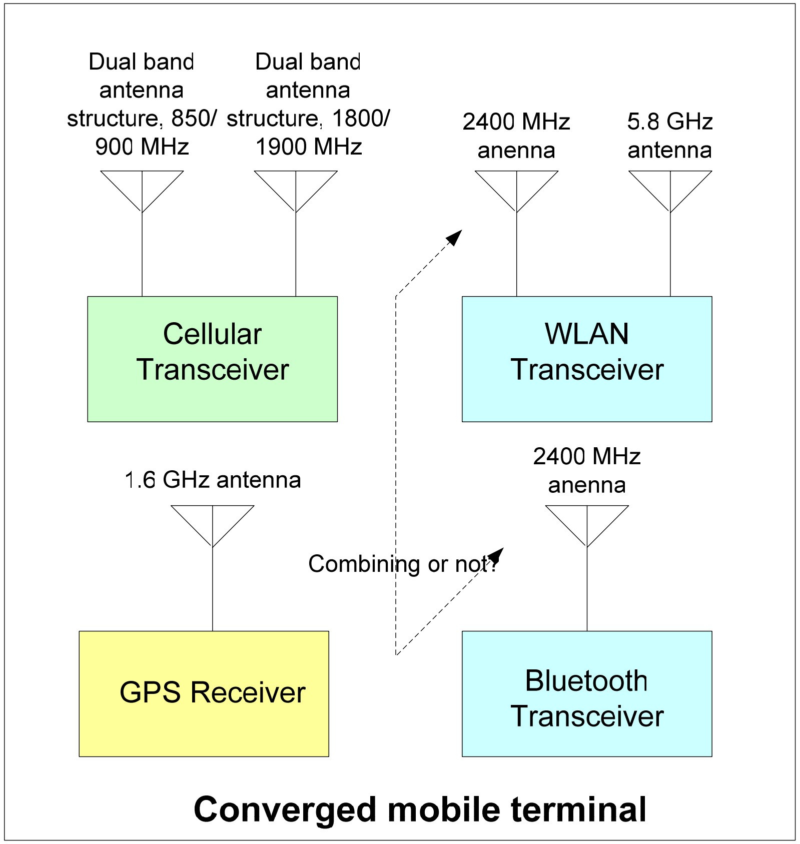
- Benefits
  - Outages reduced using information from multiple antennas/paths
  - Higher data rate and system capacity
  - Better signal quality (BER)
  - Increased coverage
- Challenges
  - Processing complexity/cost
  - Best performance requires rich multi-path environment
  - Device constraints (number of antennas, spacing, number of RF chains, coupling, etc.)
  - Network to support the technology
- Variations
  - Beam-forming MIMO
  - Phase coherency among antennas
  - Use of conversion theorem to electrically steer signal – aim signal at desired station rejecting interferers
  - Extension of existing standards
  - Spatial-multiplexing MIMO
  - Allows for multiple users by transmitting parallel data streams at the same time using spatial coding technique
  - Requires new standards (changes the format of the signal)

Multi-band Antennas

More services and smart antennas -> MORE antennas

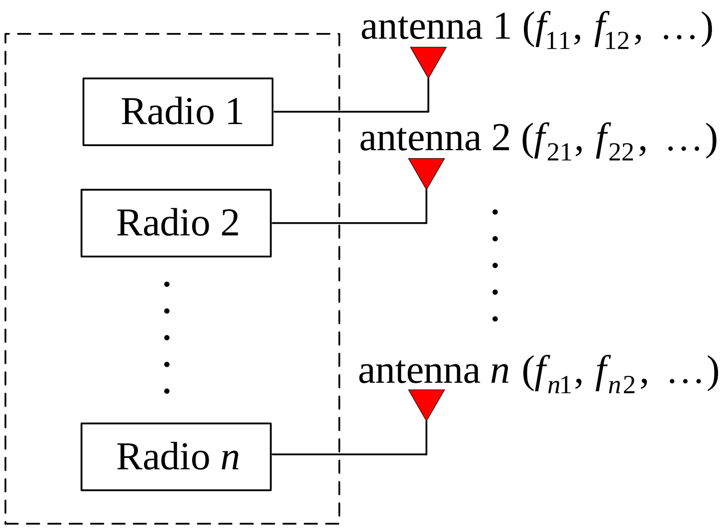
- A fundamental problem in mobile equipment implementation has *always* been where to put the antenna
- Smart antennas and convergence create new challenges
  - Converged technologies operate on new bands, implies requirement for more radios
  - Physical space restrictions limit the size/number of antennas in the terminals, especially at lower frequencies
  - Forcing a single antenna to support more radios will compromise its performance

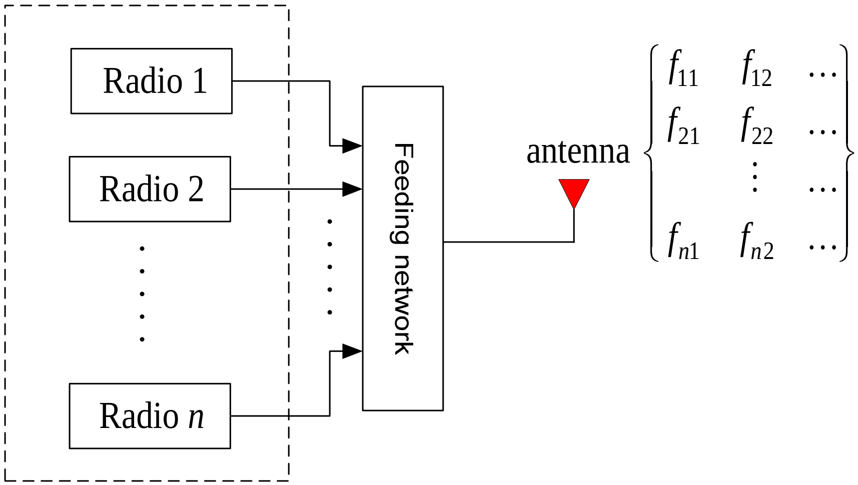
Convergence may imply a large number of antenna structures...



Single radiator, multiple feed point antennas

Alternative to conventional multiple antenna approach

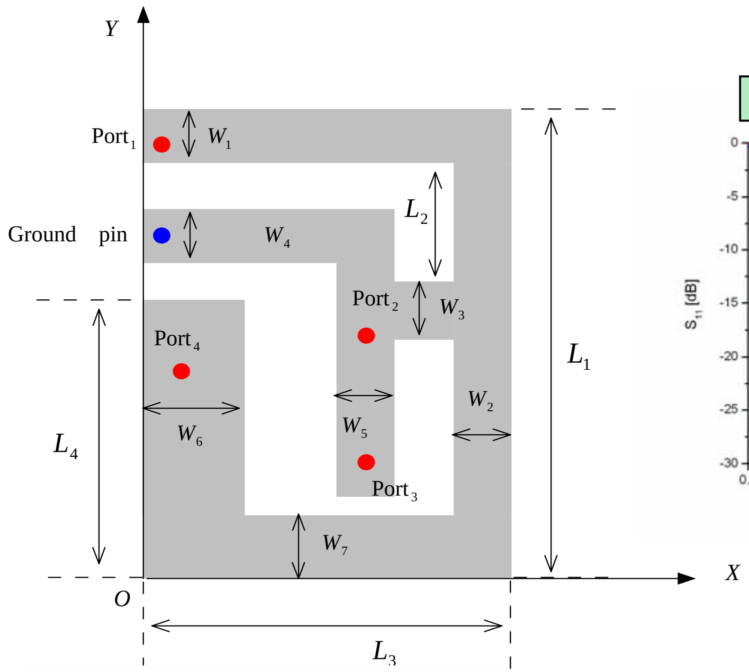




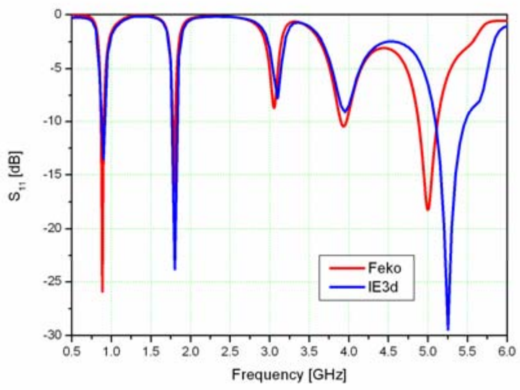
- **Conventional approach**
  - More antennas, more physical space requirements
  - Tendency toward greater EMC, EMI issues
- **Multiple feed point approach**
  - Fewer antennas, less physical space requirements
  - Gives room for multiple antennas for smart antenna processing like MIMO
  - Greater control over radiation pattern

A more practical example… 4 bands in one

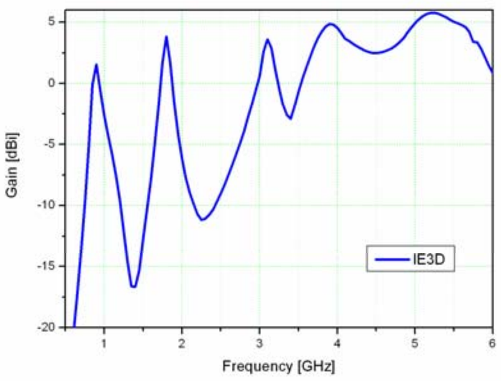
Simulation results for a 4-port prototype



Return loss over frequency

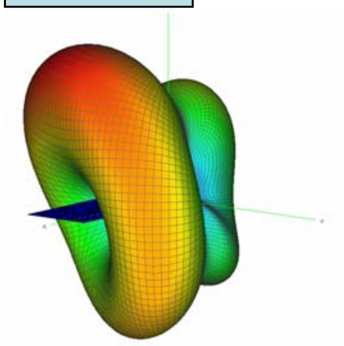


Gain over frequency

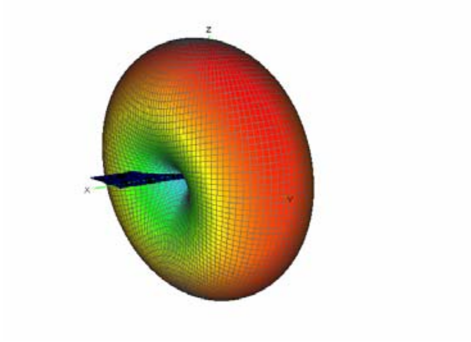


Patterns at various operating frequencies

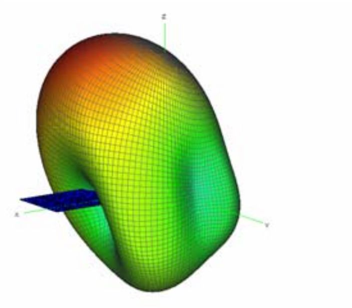
2450 MHz



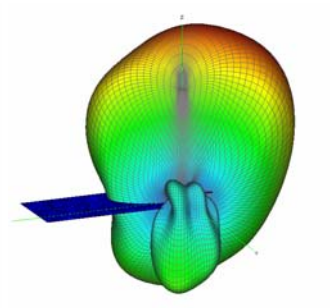
900 MHz



1800 MHz



5GHz



Summary

What we are likely to see over 10 years

- Primary technological forces
  - Radio spectrum – finite limit, expensive, scarce in densely populated areas
  - Battery life – more features consume more power
  - User mobility – uncontrolled users increase uncertainty in the management of wireless systems
- Look for technologies that ease industry constraints…
  - Flatter, less expensive, faster, more responsive system architectures
  - Information theoretic advances – push more data over the same spectrum
  - Advanced antenna techniques – cover more spectrum with less physical space consumption, smart antennas combine signal processing and electromagnetics – smaller mobile devices
  - More intelligent radio systems – better cope with user mobility and the increasing number of wireless products and users – add more users
  - Cross-layer design – optimize certain applications when used in wireless environment – better, faster data performance

It's not just about technology…

Adoption of technology involves more than just technology

- Excellent technical solutions are routinely discarded by the industry and consumers because they ignore or aggravate the non-technological forces that constrain the industry
- Standards are a double-edged sword – fuel adoption while limiting innovation: drivers or consequences
- Tomorrow's wireless technologies must consider all relevant forces
- Technology should never be an end in itself

Dialogue

How do you view these developments?

- If you were an enterprise user/customer, how would you view the wireless industry's roadmap?
  - What impact would long-term evolution have on your business objectives?
  - As user?
  - As IT department?
- If you were an IT manager, what concerns would you have regarding wireless evolution/disruption over the next 10 years?
  - Most optimistic picture of the next 10 years?
  - Most pessimistic picture?
- If you were a network operator, what would be your primary concerns over the next 10 years?
  - How would you address revenue erosion?
  - How would you charge for high-speed data?
- If you were a wireless manufacturer, what would be your primary concerns over the next 10 years?
  - Innovation space?
  - Areas of investment?
- What additional forces do you see that may have a potential impact on the wireless industry in conjunction with your own industry?

Appendix A

Comparison of voice, messaging, web and data-pipe usage

Voice - per user	Enhanced full rate	AMR 5.7 kb/s
Voice codec rate (kb/s)	12.2	5.7
Data transmitted (kbytes/min)	91.5	42.75
Minutes per month	500	500
Monthly Voice usage (Mbytes)	45.75	21.375

Messaging - per user		
Average monthly message data usage (Mbytes)(1)	2	2
(Note 1: 90% of BB users utilize < 2 Mbytes/month)		
Equivalent number of voice call minutes per month	21.857923	46.783626
Additional network capacity required (%)	4%	9%

Web surfing - per user		
Average web page size (Mbytes) (2)	0.06	0.06
Average number of accesses per day	30	30
Monthly data usage (Mbytes)	54	54
(Note 2: consensus of web page hosting firms)		
Equivalent number of voice call minutes per month	590.16393	1263.1579
Additional network capacity required (%)	118%	253%

PC Card Data - per user		
CNN News Website (Mbytes)	0.4	0.4
Number of websites per day	1	1
Download email per day (Mbytes)	1	1
15 min/day streaming video, (Mbytes)	57.6	57.6
Total monthly data usage (Mbytes)	1770	1770
Equivalent number of voice call minutes per month	19,344	41,404
Additional network capacity required (%)	3869%	8281%

Mark Pecen

- Mark Pecen serves as Vice President, Advanced Technology for Research in Motion Limited (RIM), makers of the BlackBerry wireless devices, systems and services. He is responsible for long-term corporate strategy for advanced wireless technology investments, commercialization of applied research and customer collaboration on future technology deployment.
- Pecen is the founder of the RIM Wireless and Networking Advanced Research Centre and founder of RIM CTO Board. Current priorities include development of technologies for the evolution of existing and creation of Next Generation wireless systems. His labs are active in applied information theory, smart antennas, cross-layer wireless network design and protocols, mobility management, radio link control, statistical analysis and simulation and modeling of wireless systems.
- Prior to joining RIM in 2005, Pecen held the title Distinguished Innovator and Science Advisory Board Associate (SABA) member, representing the top 1% of technology leaders at Motorola, Inc. Since 1988, Pecen has invented a number of technologies adopted in global standards for the Global System for Mobile telecommunication (GSM), General Packet Radio Service (GPRS), Enhanced Data for GSM Evolution (EDGE), Universal Mobile Telecommunication System (UMTS) and various Wireless Local Area Networks (WLAN) standards.
- He serves on the boards of several technology-focused industrial, academic and governmental associations in North America and Europe and is the board chairman of Quantum Works, a consortium that funds and manages applied research into quantum computing across a network of universities in Canada.
- Pecen holds more than 70 patents in the areas of mobile communication, networking and computing, and is a graduate of the University of Pennsylvania, Wharton School of Business and the School of Engineering and Applied Sciences.