# The impact of emerging receiver technologies on changing standards and spectrum allocations

A brief study
by the
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# Disclaimer

- The purpose of this study is to inform and educate FCC staff and TAC members about emerging receiver technologies
- References and citations in this study are for educational and informational purposes only and are not directed to the merits of the work or sources being referenced
- The study is the work of the individual authors and it does not necessarily reflect the opinion or views of their employers or the views of the Federal Communications Commission

# Overview

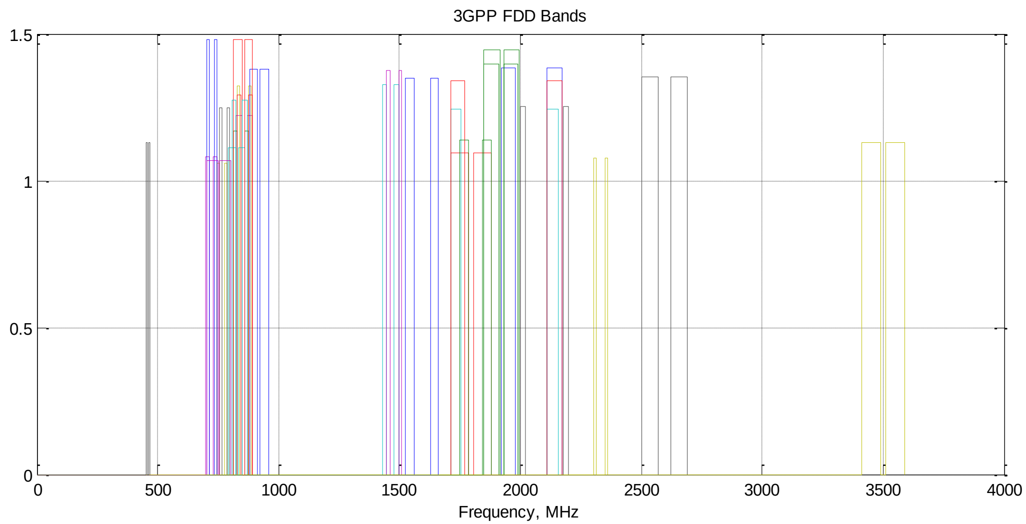
- A brief examination of several emerging receiver technologies…
  - Receiver Hardware Technologies
    - Advances in hardware components that allow improved receiver tunability, selectivity, or dynamic range
    - Potentially allows tighter service packing / reduction of guard bands
  - Dynamic Interference Mitigation Techniques
    - Wide range of methods and algorithms to reduce the impact of interference, including beam-forming and self/cross-interference reduction techniques
    - Can increase system capacity and allow tighter spectrum packing
  - Software Defined Radio Technologies
    - Highly flexible re-programmable radio designs, that allow a wide range of operating modes, upgradeability, and in some cases superior performance
    - Some re-programmability often utilized in baseband domains (e.g., DSPs, etc.)
    - Desire to move ADCs further up the receive chain…
    - Typically better suited for certain use cases (e.g., that are less power constrained)

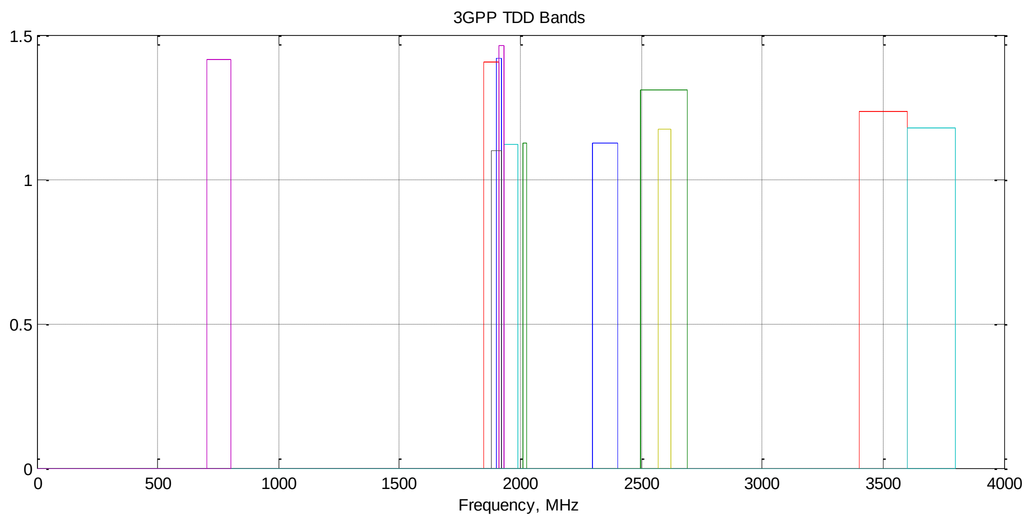
# One Driving Trend: Spectral Crowding


- Spectrum usage becoming increasingly crowded…
  - Mobile data (e.g., smartphone/smart device) revolution
  - Many pieces of spectrum being re-purposed and/or expanded (e.g., National Broadband Plan)
  - Shared spectrum techniques emerging to more thoroughly utilize spectrum (e.g., TVWS, 3.5GHz)
- Many nearby disparate users of spectrum…
  - Increases opportunities for interference (e.g., especially with mixtures of larger/smaller area networks, high power/low power networks, highly sensitive/less sensitive receivers, etc.)
  - Increases receiver demands in terms of dynamic range and frequency selectivity

# Another Related Trend: Standards Band Proliferation

- 3GPP LTE bands (40+) example >
- Natural consequence of…
  - International (disparate) regulation
  - Mobile data revolution
  - Crowded spectral environments
- Tends to drive…
  - Multi-band transceiver technologies
    - Unified RF arch., where possible
    - Often cost or performance constrained
  - Interference Management
    - Improved Tunability / Selectivity
    - Interference mitigation techniques
- Doesn’t even include multitude of other bands
  - Unlicensed (WiFi/BT), GPS, etc.
  - Carrier aggregation for higher capacity or QOS



# Some Other Considerations…

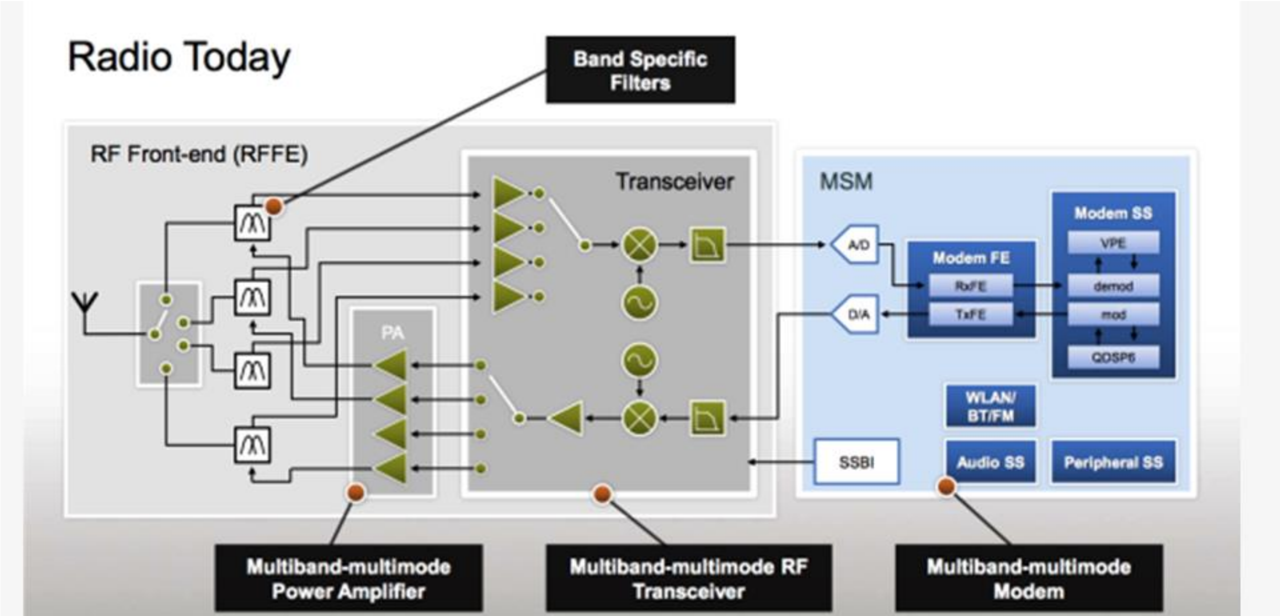
- Several other factors come into play when making technology choices…
  - Economies of scale in deploying new technologies…
    - Difficult to quantify – not directly addressed in the study
  - Often difficult to separate technology decisions from target markets…
    - Particularly challenging for low cost markets (e.g., GPS, WiFi, etc.)
      - Cost may impact success in consumer markets (e.g., may also call for low-spec radios…)
    - Handheld/battery-powered mobile devices are also challenging cases…
      - Energy limitations (limited battery volume)
      - Antenna limitations (handheld & mobility challenges)
      - Cost limitations (& possible volume requirements/dependency)
  - Some applications are better suited for technology advances…
    - Infrastructure equipment (e.g., base stations, broadcast transmitters, etc.)
      - Not as power and size limited
      - Not as cost-constrained
      - Have seen some of these trends in the industry (e.g., SDR in cellular BSs, DTV transmitters)
    - Fixed consumer equipment (e.g., fixed wireless access point, DTV receivers)
      - Not as power limited
      - Though likely cost-constrained at different levels

# Further Considerations…

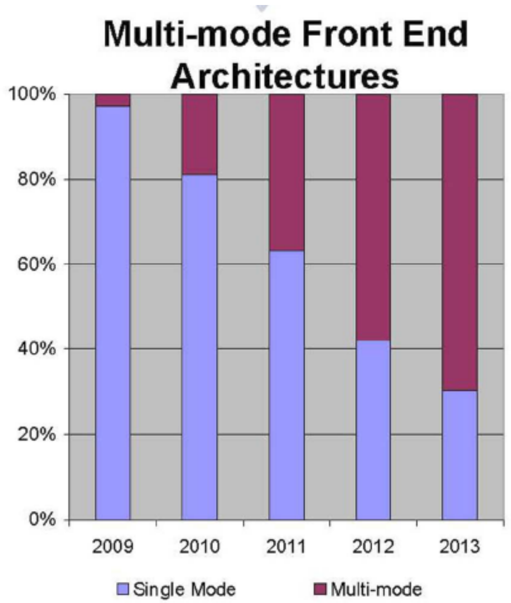
- Advantageous to provide natural incentives for better performance…
  - Consumers and corporations need to see some of the benefits of the new technologies…
    - Better performance in crowded spectral environments (but often lost on consumers)
    - Frequency agility to operate in one or more of many possible bands…
      - Multi-band radios - potentially higher QOS (utilizing spectrum with lowest interference)
      - Carrier aggregation / simultaneous carriers – higher throughputs (also drives linearity)
    - Interference mitigation techniques
      - Generally increase capacity by reducing interference (e.g., beam-forming/pre-coding/IC) and providing additional spatial resources (e.g., SU-MIMO)
    - Dynamic Spectrum Access systems offer the possibility of highlighting better performance
      - In DSA systems, better transceivers allow higher TX power levels, additional operating areas…
  - Development of Interference Limits Policy…
    - Harm Claim Thresholds to help determine cases of harmful interference
      - Multi-stakeholder groups to help develop (e.g., in 3.5GHz band)
  - Economic incentives often the strongest motivators…
    - CMRS – goal of maximizing capacity per unit area (of limited resources/assets)
    - Goals may be different for other services (e.g., coverage/reliability over cost in PS systems)
    - Energy consumption also becoming a strong motivator (e.g., ‘green’ base stations, 5G stds.)

# Receiver Hardware Technologies…

# Typical Receiver Design



(QCOM)



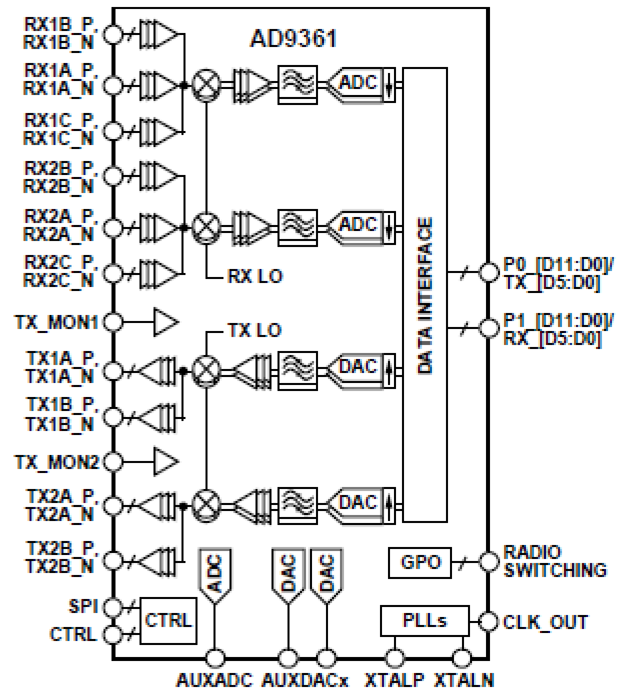
(RFMD)

- Traditional higher volume multi-band radio designs…
  - Often employ band-switching architectures to achieve linearity/performance goals…
    - Utilize band-specific (SAW/BAW) filters for cost & performance (e.g., cellphones)
      - Excellent selectivity, size and cost - good IIP3 performance levels (true of switches as well)
      - Resonator SAWs typically used in duplexers (though typ. have limited passband power handling)
    - Direct conversion architectures also popular…
      - Highly flexible in terms of operating frequency and bandwidths
      - High levels of integration possible - cost effective

# Highly Integrated Transceivers

- High performance highly integrated commercially available RF transceiver ICs
  - Offer good performance in small packages…
    - Multi-channel direct conversion arch. (e.g., 2x2) w/PLLs/LOs & ADCs/DACs (incl. AGC)
    - Wide operating frequency range (e.g., ~100MHz-6GHz) and channel BWs (~200KHz-50MHz)
    - Good noise figure (~3dB, not incl. band filtering)
    - Decent linearity (-15dBm IIP3@max gain)
    - Used in commercial SDRs (e.g., USRP)
    - Though costly (targets certain base stations)…
  - Several companies do custom IC work in these areas…
    - Many large equipment providers take this approach…
  - Subject area of much research
    - See also Klumperink IEEE DySpan 2014 tutorial

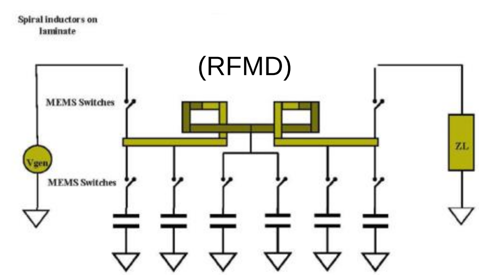
FUNCTIONAL BLOCK DIAGRAM




(Analog Devices)

# MEMS Technologies

- High performance RF Micro-Electro-Mechanical-Systems (MEMS)
  - Some potential radio applications…
    - RF switching (MEMS contact switches - e.g., for multi-band filters)
    - Tunable filters (e.g., capacitive MEMS switches)
  - MEMS RF (multi-pole/multi-throw) switches…
    - Offer improved IIP3 performance (>10dB) over solid state switches
    - Potentially Lower insertion losses / Higher isolation than SSSs
    - Relatively slower (~50x) than SSSs / Higher activation voltage (~30-100v) / Limited lifetime
    - Generally slightly more costly (less so at higher throw counts)
    - Showing yearly improvements in technology
  - MEMS tunable filters (capacitive MEMS)…
    - Tunable filters for antenna matching and notching
    - Often consists of banks of two-state capacitors
    - Fairly wide tuning ranges – moderate filter Qs obtainable
    - Excellent IIP3 performance possible (~80dBm)
    - Technology improving over time…




Tuning range from 700 to 2 GHz

- Other materials research on the horizon…
  - Nanostructured materials like multi-layer crystals (self-correcting tunable dielectrics)…
    - Engineered low-power high-frequency devices w/high tunability and low loss

# Tunable Filtering

- Developing area: Tunable N-path filtering architectures…
  - Form of tunable filtering with center frequency reliant on (phased) clock rate…
    - Fewer trade-offs than active transconductance BPFs (Pd vs. DR, Fc vs. Q)
    - Good dynamic range performance theoretically possible
    - Low noise figures possible (though moderate power consumption)
    - Can be implemented in CMOS processes

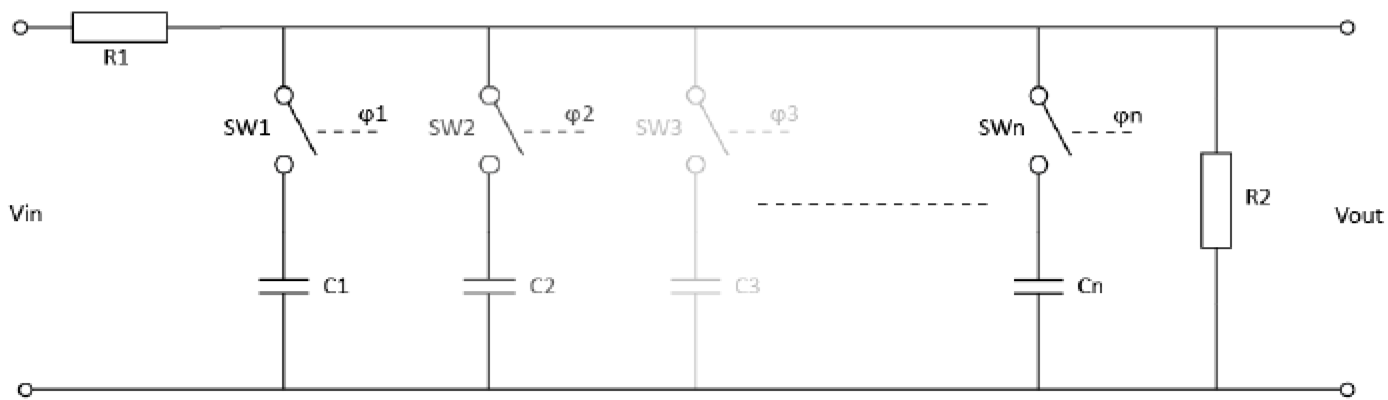



Figure 4 - N-path filter used by Frischl [3]. This circuit is an efficient implementation of a RC N-path filter. R1 and the capacitors form the RC low-pass network. The switches act as both the input and output mixers.

(Fortgens)

# Dynamic Interference Mitigation Techniques…

# Dynamic Interference Mitigation Topics

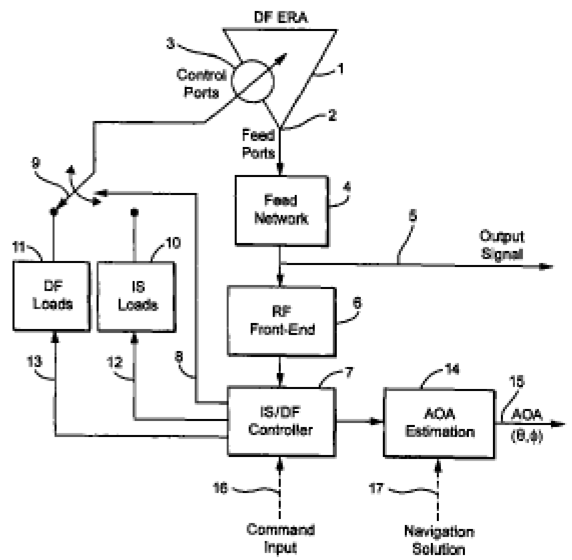
- Beam Forming
  - Increases signal strength over desired communications paths…
- Null Steering
  - Decreases received signal strength from identified interferers…
- Self Transmission Cancellation
  - A transceiver that cancels its transmitted signal at its receiver to permit full duplex communications on a single frequency channel…

# Dynamic Beam-Forming / Null-steering

- Ezal *et al.* – Uses polarization sensitive antennas plus angle of arrival techniques to identify interferers and then null their signals
- Vosburgh *et al.* – Continuous Adaptive Interference Nulling (CAIN) method tracks moving interferers and reduces interference by 30 dB
- Vosburgh *et al.* – Addition of Advanced Field Nulling (AFN) method to the CAIN method reduces interference another 10 dB
- Motorola Solutions – 4G beam forming video demos
- Coordinated Multipoint (CoMP) is proposed for the new LTE-Advanced standard and decreases interference at the edges of cells
- Distributed Input Distributed Output (DIDO) encodes all signals received at one base station specific to their locations and when all signals are added together at one location the interferers cancel

# Beam-Forming / Null-steering Technologies (1)

- Non-phased antenna that is polarization sensitive with an angle of incidence detector is used to identify interferers and their directions. This information is then used to cancel the interfering signal




Ezal KO, Larry TL, Richen AS, Wiatt MR, Agate CS, Werner BD, Vanblaricum ML [2009]: Compact Antenna System for Polarization Sensitive Null Steering and Direction-Finding, US Patent 7577464

# Beam-Forming / Null-steering Technologies (2)

- Continuous Adaptive Interference Nulling (CAIN) method reduces interference by 34 dB

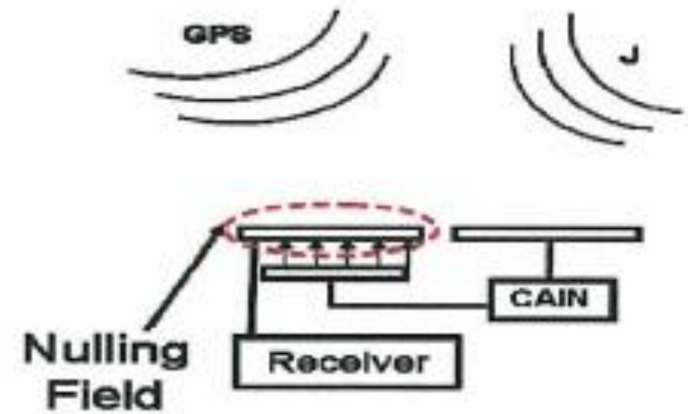



Figure 9 CAIN variant using a backplane emitter to induce an antenna field with jamming content anti-phase aligned to the field induced by the jammer (J) to block GPS jamming, vs. removing it after the fact.

b)


Figure 11 Field Nulling blocks jamming; a) jammed signal, b) nulling of jammer

Figure 11 blocking of broadband jammer; a) jammed signal, b) result of blocking an over-air CDMA jammer at -78 dBm which masks a separately transmitted tone at -97 dBm using the test configuration diagramed in Figure 9. As the figure illustrates, the masking signal is reduced to -112 dBm yielding an SNR improvement of 34 dB.

Vosburgh R, Wilson C, Haridasan V [2013]: Cancellation of in-band jamming for robust GPS navigation, *ION ITM*.

# Beam-Forming / Null-steering Technologies (3)

- Advanced Field Nulling (AFN) combined with the CAIN method reduces interference by 40 dB

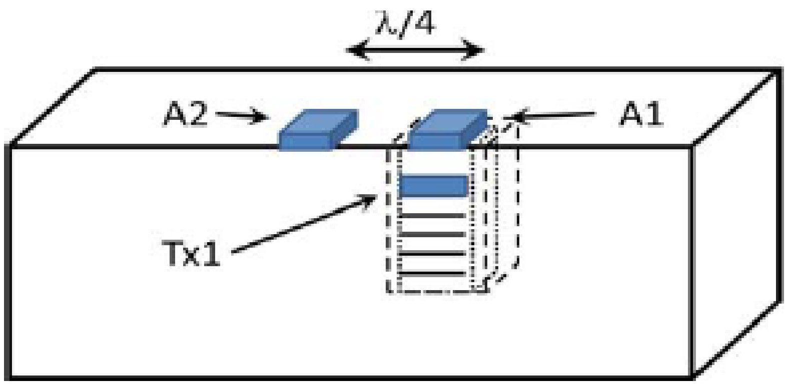



Figure 1b mounting of antennas in figure 1a, including the A1-Tx1 induction stack and secondary antenna A2 providing signal for field nulling.

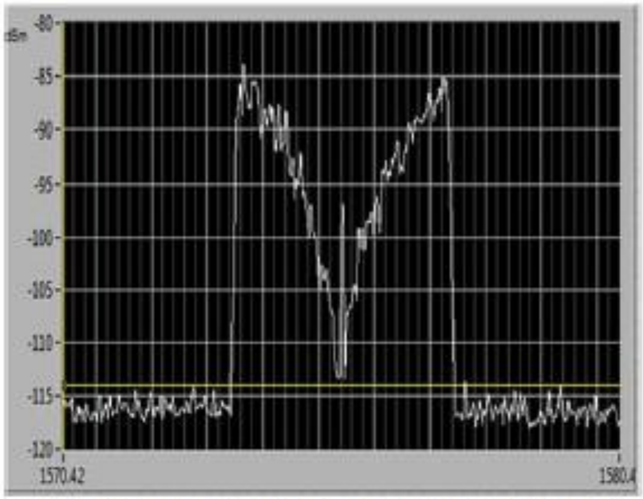
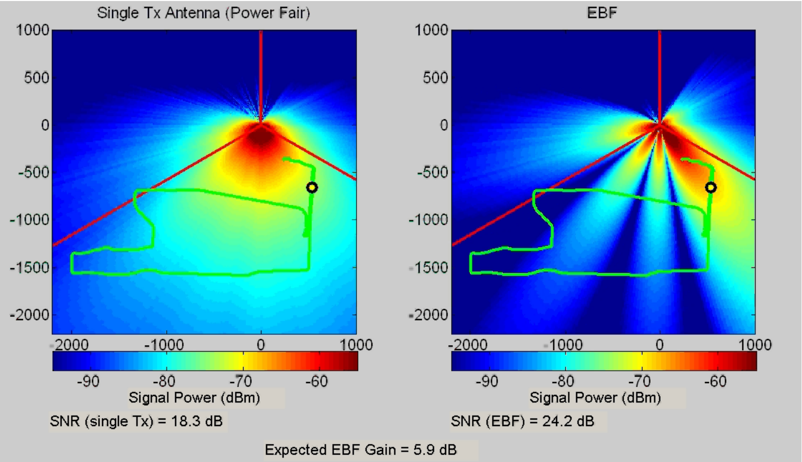


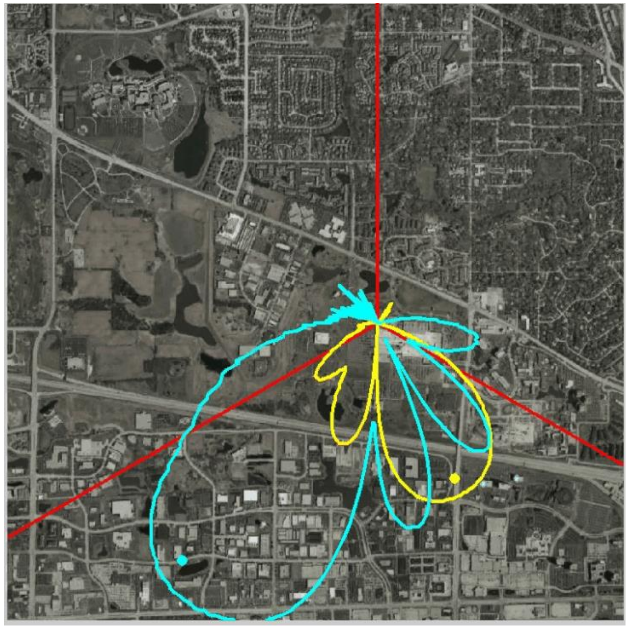

Figure 5: VSA screen capture of AFN at 1.575 GHz showing 40 dB reduction in wideband jamming.

Vosburgh R, Haridasan V, Wilson C [2014]: Continuous Adaptive Interference Nulling for Defeat of Wideband GNSS Interference, *ION GNSS*.

# Beam-Forming / Null-steering Technologies (4)

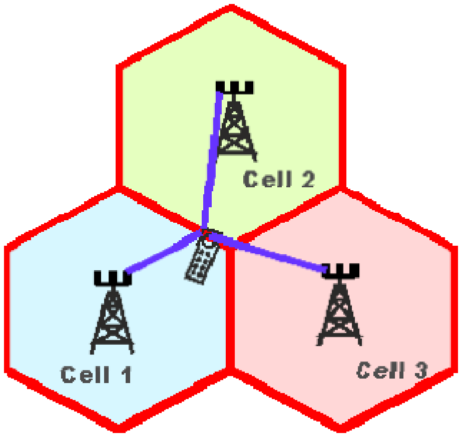
- Past Motorola Adaptive Antenna research demos/visualizations…
- Use antenna arrays and pre-coding/beam-forming to improve received signal SINRs
  - Real-time visual beam-forming demo…
    - Drive test of MSI 4G OFDMA TDD system using over-the-air test system in Schaumburg, IL
    - Operating in the 3.4GHz band
    - 4-element antenna array (per sector)
    - ~35 m antenna ht. / ~55 dBm max EIRP w/power control
    - Yellow and Blue circles indicate location of drive test vehicles (green test route)
    - Note real-time gains of beam-forming over single antenna case (power-fair)
    - Note real-time desired user beam-steering and null-steering towards other (undesired) users



# Coordinated Multipoint Technologies

- **LTE Coordinated Multipoint Technologies (CoMP)**
- Improves spectrum utilization and data rates at the edges of cells, where interference from adjacent cells is the greatest
- Intercommunication between base stations selects one or more base stations to communicate, using beam forming and null steering to minimize interference, or joint TX/RX processing



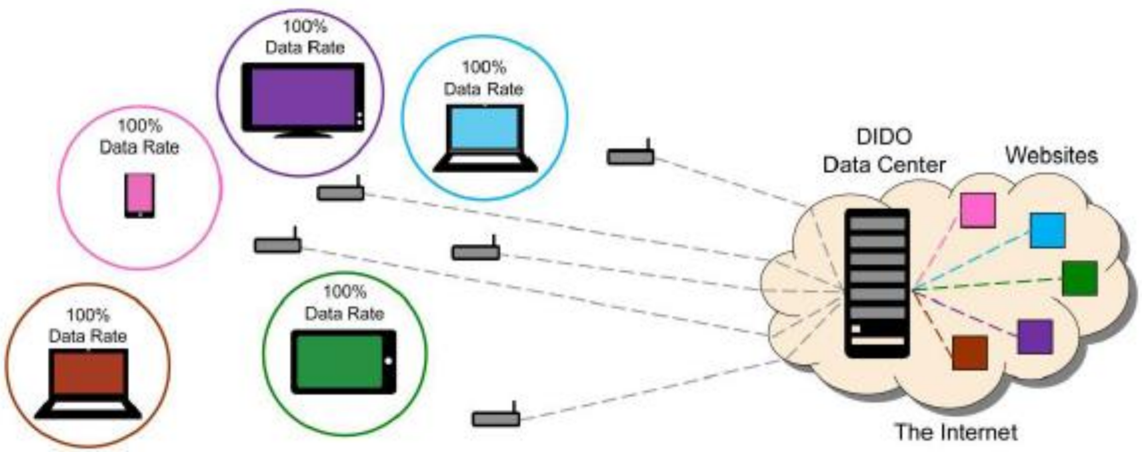


•3rd Generation Partnership Project [2011-12]: Coordinated multi-point operation for LTE physical layer aspects (Release 11), 3GPP TR 36.819 V11.1.0.

•IEEE [2011]: Standard for Local and metropolitan area networks, Part 16: Air Interface for Broadband Wireless Access Systems, Amendment 3: Advanced Air Interface, *802.16m-2011*.

# Distributed Input Distributed Output Techniques

- **Distributed Input Distributed Output (DIDO) Technique**
- Each user's waveform is encoded into a distinct waveform specific to the relative locations of the users and the communicating node
- At each user location, when all the encoded waveforms are added together all other waveforms cancel
- As users leave the area, or new users arrive, and as users move around, the full set of encoded waveforms is recalculated to continue to cancel interference at each user location




- Perlman S, Forenza A [2011]: Distributed-Input-Distributed-Output (DIDO) Wireless Technology. A New Approach to Multiuser Wireless, www.rearden.com

# Full Duplex Techniques

- Methods that cancel the transmitted signal at the receiver allow simultaneous transmit and receive on the same frequency channel
- Potential doubling of spectrum use
- Everett isolates transmit from receive by using directional antennas
- Choi uses phased antennas to cancel the transmitted signal at the receiver
- Bharadia -> Kumu Networks uses a sample of the transmitted signal to null it at the receiver input. Demonstrated -110 dB isolation in WiFi systems and -140 dB isolation in LTE repeaters
- TrellisWare transmits jamming signal and uses its pattern to cancel its effects at the receiver

# Full Duplex Technologies (1)

- **Isolating transmit from receive by using directional antennas**.
- Far less expensive than performing analog cancellation, and nearly as much of a data rate improvement

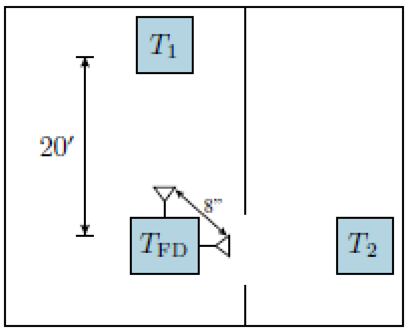


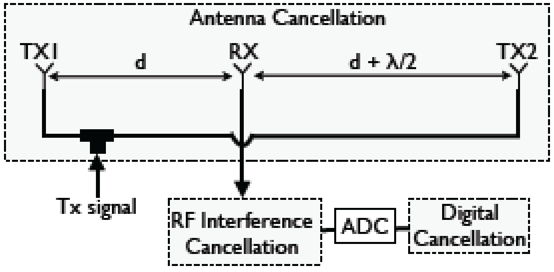

TABLE I: Two-Hop Network Achievable Rates.

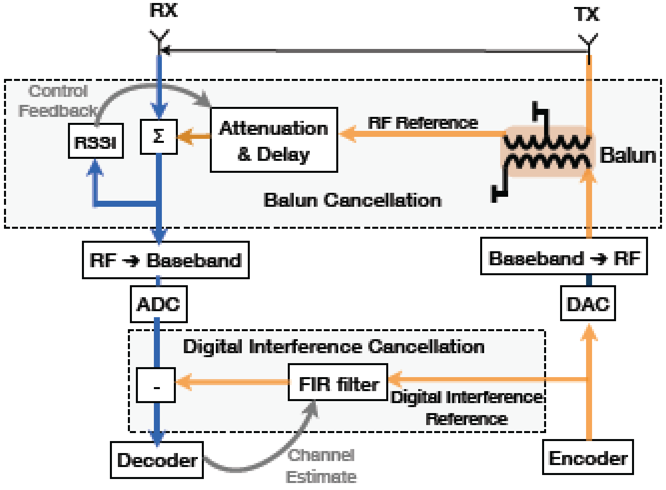
| | End-to-end Achievable Rate | Rate Improvement over HD |
|---|---|---|
| Half-Duplex | 4.76 bits/s/Hz | – |
| FD w/o Analog Canc. | 7.70 bits/s/Hz | 62 % |
| FD w/ Analog Canc. | 8.27 bits/s/Hz | 74 % |

- Everett E, Duarte M, Dick C, Sabharwal A [2011]: Empowering full-duplex wireless communication by exploiting directional diversity, *Asilomar Conf on Signals, Systems, and Computers*.

# Full Duplex Technologies (2)

- Combination of three cancellation techniques: Antenna Phasing, RF Interference Cancellation, and Digital Cancellation

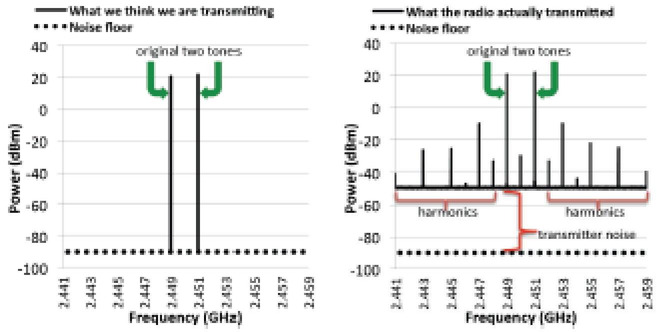


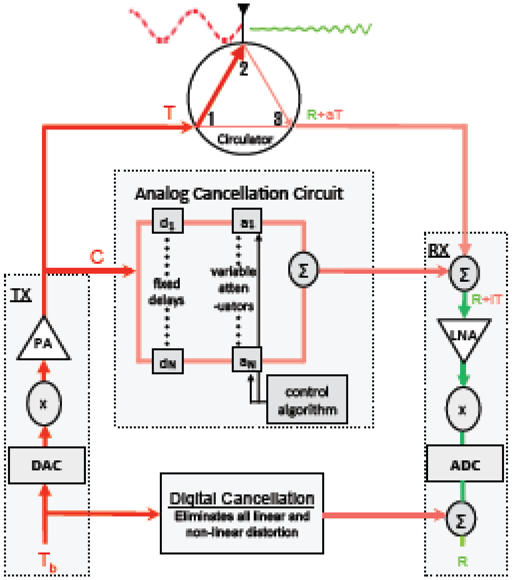




Jain M, Choi JI, *et al.* [2011]: Practical, Real-time, Full Duplex Wireless, *Proc Intl Conf Mobile Computing and Networking (MobiCom)*.

# Full Duplex Technologies (3)

- A sample of the transmitted signal is used to null it at the receiver input
- Demonstrated -110 dB isolation in WiFi systems

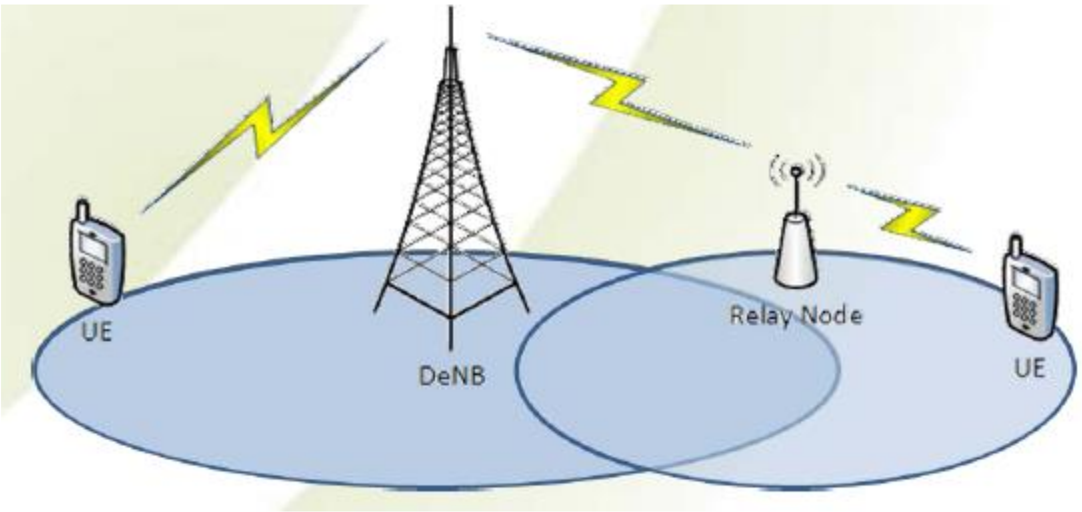



Bharadia D, McMilin E, Katti S [2013]: Full Duplex Radios, *ACM SIGCOMM*.

# Full Duplex Technologies (4)

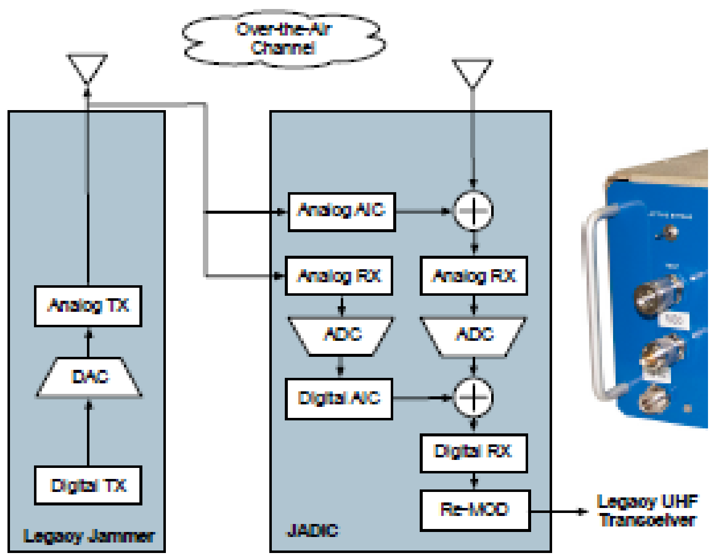
- A sample of the transmitted signal is used to null it at the receiver input
- Demonstrated  -140 dB isolation in full duplex LTE-Advanced Relay Nodes




Kumu Networks [2014]: Self-Backhauled Small Cell White Paper.

# Interference Cancellation Technologies

- TrellisWare Technologies uses Joint Analog and Digital Interference Cancellation (JADIC)
- Introduces a jamming signal onto a frequency channel and uses a sample of that signal to cancel it so that channel can still be used for communication

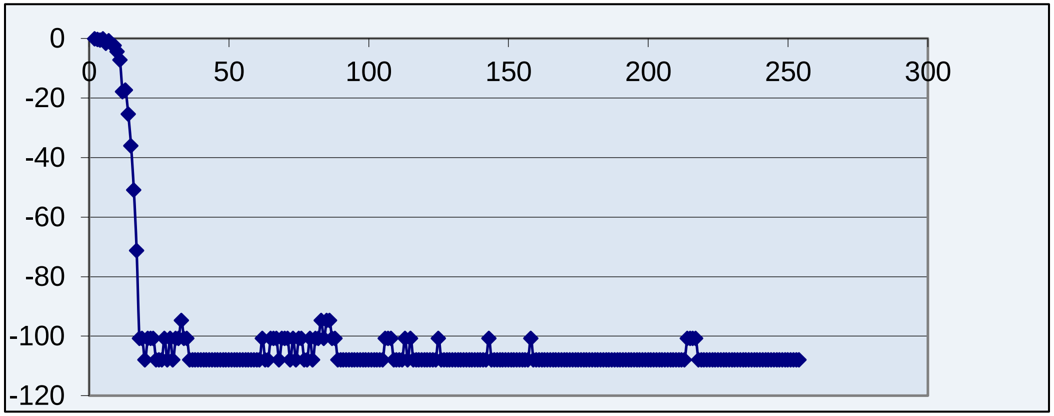



Enserink S, Fitz MP, *et al*., [2014]: Joint Analog and Digital Interference Cancellation, *DySPAN*.

# Software Defined Radio (SDR) Technologies…

# Software Defined Radio (SDR) Technologies

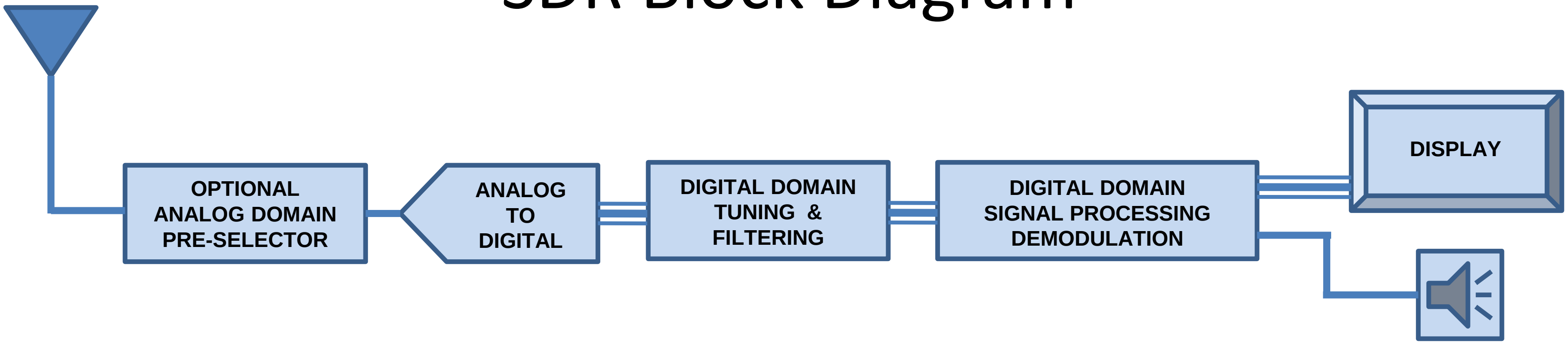
- Virtualizes hardware functions into software functions executing real-time (or near real-time) applications
- Many baseband functions today already performed in part by some type of programmable platform
- Upgradability --> Architecture/function of SDR can be changed by changing firmware
- SDR field upgradable to new spectrum allocations, modulation standards, etc.
- Firmware update can be via Internet, USB, or “over-the-air” (OTA)
- Performance of SDR set by accurate digitization of analog signals over wide dynamic range
- Direct digitization of RF frequency ranges now possible (e.g., giga-sample converters)
- Eliminates down-conversion to intermediate frequency and the intermodulation performance limitations of down-conversion architectures
- AGC-free dynamic range of SDR architectures is a key performance measure
- Digital filters offer higher performance than possible with analog filters…




100dB/octave Stable and Repeatable Filters possible!

# Software Defined Radio (SDR) Technologies

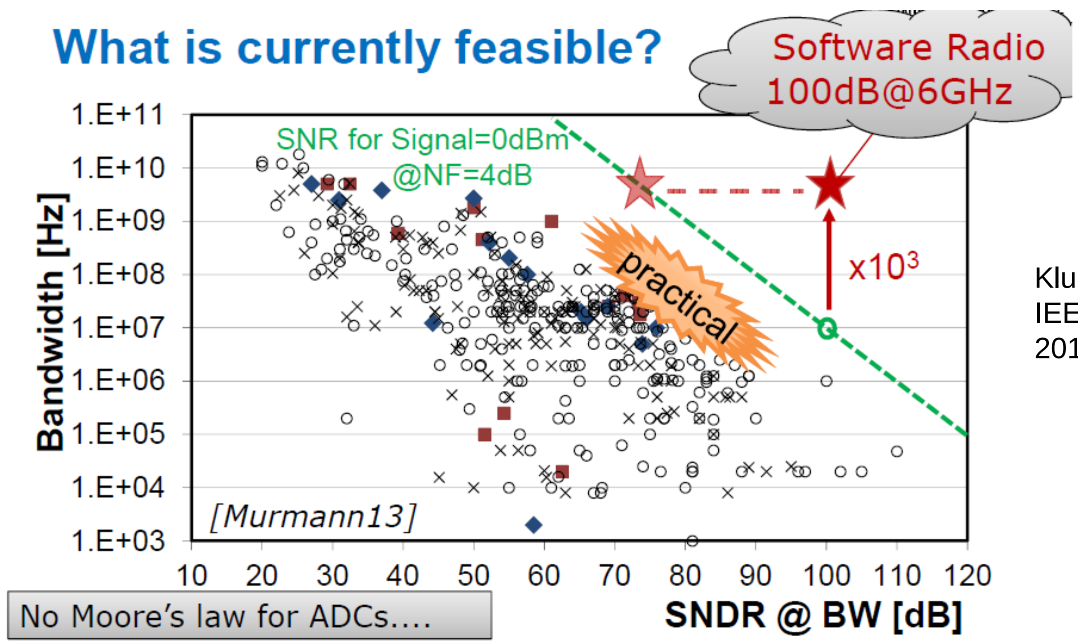
## SDR Block Diagram




(ideal SDR)

# SDR ADC Technologies

- High performance ADC technologies are becoming more widely available…
  - Dynamic range, sample rates, cost and power are keys to performance
    - Aside from Effective Number of Bits (ENOB/SINAD), Spurious Free Dynamic Range (SFDR) is key in SDR ADCs
    - Any RF components ahead of converters (e.g., LNAs, filters) need superior linearity performance (in wideband/broadband receivers)
    - Sub-band sampling techniques allow lower conversion rates (saving power)
    - Over-sampling allows digital filtering processing gain (to overcome quantization noise)
    - Cost and power still challenging…
  - See ADC performance comparison study…
    - See [http://www.stanford.edu/~murmann/adcsurvey.html](http://www.stanford.edu/~murmann/adcsurvey.html)




Klumperink
IEEE DySpan
2014 tutorial

# Software Defined Radio (SDR) Technologies

- Systems on a Chip (SoC) - Hybridization of FPGA and processor core technology may reduce overall system cost while still allowing firmware upgradability
  - Latest FPGAs integrate RISC processor cores along with programmable logic (e.g., Xilinx Zynq FPGAs with dual-core ARM A9 processors)
  - FPGAs often are fabricated with the latest (cutting edge) process technology (e.g., Xilinx Virtex 7 FPGAs built on 28nm process technology, etc.), reducing power consumption and increasing density
- Fixed devices are better near term candidates for the application of SDR technology
  - Examples: cellular infrastructure transceivers, public safety/wireless base stations, consumer digital television and digital radio sets
  - Ongoing field software updates allow regulatory changes without requiring obsolescence of existing equipment
- SDR technology, in particular, offers the promise of allowing certain receivers to adapt to changing modulation standards and spectrum allocations while avoiding the limitations formerly imposed by legacy receivers

# Concluding Thoughts

- Opportunities for highly efficient spectrum usage…
  - Several emerging technologies were highlighted that may improve receiver capabilities or performance to allow more efficient use of spectrum
    - Many technologies are available today, or are under current development…
    - Cost seems to be one of the most challenging barriers (for some technologies)
  - For best results, emerging technologies should be supported in standards to achieve widespread industry buy-in…
    - Many successful technologies are standards-endorsed and/or driven
      - Some examples include MIMO and beam-forming techniques
    - Ensures wide adoption of technology, lower costs, as well as future enhancements…
  - Component technologies will continue to advance over time…
    - Natural trend in component technology (performance improvements over time)
    - Economics plays an important role, especially in high volume designs
  - SDR technology enables receivers to adapt to changing modulation standards and spectrum allocations avoiding limitations imposed by legacy receivers
    - Useful for applications that can support the additional cost and power consumption
  - Various technology trade-offs often are not simple…
    - Often highly involved multi-variable design trade-offs – difficult to generalize…
    - Difficult to generalize and extrapolate trends (often economic or problem driven)…
  - The FCC should facilitate emerging technologies wherever possible…
    - Not the same as trying to pick technology winners and losers
    - Encourage testing/proving grounds for new technologies (e.g., DSA technologies, etc.)

# References


- 3rd Generation Partnership Project: Coordinated multi-point operation for LTE physical layer aspects (Release 11). 3GPP TR 36.819 V11.1.0, 2011-12.
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