Raytheon BBN Technologies
A Testbed to Enable A Wireless Revolution

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THE CHALLENGE
Wireless is Our Future

Over 10B WiFi chipsets had been sold as of early 2015

Over 3B Bluetooth and 3B WiFi chipsets were sold in 2015 alone

Increasingly, wireless is the only way people communicate

And every year each person communicates (on average) a lot more

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Figure. Percentages of adults and children living in households with only wireless telephone service: United States, 2003–2014

Chart III.C.2
Mobile Data Usage per Subscriber, 2010 - 2013

Sources: HHS CDC Health Interview Survey 12/2014; FCC Mobile Wireless Report 12/2014

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Yet We Don’t Use Spectrum Effectively

Most of the spectrum is horribly underutilized

We divided up much of the spectrum in ways that made sense at the time, but increasingly does not make sense now.

Similarly, data caps and such like are a symptom of scarcity, which has several causes, but one cause is poorly used spectrum.

The controversy over 5G and white space is an example of demand pressures causing fights about over too little and/or poorly used spectrum.
Fixing This Situation: Ideas

- We are rich in basic research ideas for fixing this situation
  - Directional radios
  - Signal strength/power management
  - Better coding
  - Spectrum agility
  - Using more spectrum bands when they are otherwise idle

- These ideas generally require sophisticated, highly programmable radios

- Right now, radios incorporating many of those ideas cost between $1k and $5K

- But by the late 2020s (or sooner) they’ll be approaching pricing consistent with the consumer market

Analog and Digital Logic Cost Curves (from $1.5K)
Fixing This Situation: A Testbed

• Given a lot of good ideas that need wider testing and exposure, we’ve historically had success creating large experimental spaces, usually called “testbeds”*

• Mix thousands of cutting edge users with researchers and leading edge tech companies
  – A “Show Me” environment, where ideas have to prove themselves
  – User who live in the future, developers who program the future, and potential vendors who see the future

• Examples
  – Operating Systems (BSD Unix)
  – Networking (Internet and NSFNET)
  – Gigabit Testbeds
  – Graphics and personal workstations (Project Athena)

• The Pattern of Success
  – Research community leads
  – Someone operates it
  – Easy for industry to join in
  – Pace of innovation picks up sharply about 2 years in

*Somewhat confusingly, we also use the word testbed for small test environments
Create Nationwide Wireless Testbed

• Give every PhD student in CS and EE a cutting edge experimental radio (a radio 15 years ahead of today’s best commercial stuff)
  – Expose our best and brightest young talent to the future of wireless
  – Put experimental base stations on their campuses
  – Connect via high speed research infrastructure (e.g. Internet2/GENI/Pacific Research Platform)
  – Leverage broad FCC experimental licenses to university campuses to enable a wide range of experiments
  – Instrumented for experimentation

• Make it easy for industry to join too!
Making a Testbed Work

- Testbeds are the best approach in a world full of ideas that need larger exposure and testing

- But testbeds have risks, including:
  - Execution failure -> testbed doesn’t get built
    - We will need an experienced leadership team
  - Technology failure -> no one wants to experiment with the testbed
    - Make sure the technology is exciting! A radio 15 years in the future
  - Exclusion failure -> keeping the population small and exclusive, rather than encouraging participation
    - Every PhD student in CS and EE
    - Easy for industry to join
A Bigger Picture

Big DataCenters/Clouds

Backbone Nets

Edge Cloud

5G’s sweet spot

Edge Cloud

Base Station

Internet of Things

This effort’s sweet spot

Images courtesy: FreeDigitalPhotos.net

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A Radio to Every EE/CS PhD Student

- Out of the box: faster and more robust connectivity than they’ve ever had
- An Open Research Platform
  - About the size of a tablet
  - Open hardware; refreshed every 3 years
  - Open software; regular small releases; big release every 18 months
  - Ability to replace some antenna and hardware modules
- Multiple base stations for each university
  - Runs same code as individual radios
- Easy to purchase additional radios
- License under FCC 5.301-311 allowing general experimentation across the RF spectrum on university campuses
  - Industry can join if manufacturers devices that incorporates radio frequency equipment (5.302) or by creating an innovation zone (5.313)
Imagine a Wireless Infrastructure to Match the Wired Research Infrastructure
An Environment for Sharing

• A good platform creates an environment of sharing and “show me” experimentation

• Source and hardware open for research
  – No restrictions on research use [see licensing later]

• People swap code or hardware versions until it starts working the way they intend
  – Best ideas get rolled into releases to everyone

• Research results are valid only when actually implemented and shared so others can replicate the result
  – A tremendous problem in wireless today
Experimentation

• The goal is to enable a range of research in the sciences
  – Bandwidth for data is essential to large range of scientific activities in fields such as archaeology, astronomy, medicine and physics.
  – Sometimes having a wire or cable is a hindrance

• Also research in data communications and distributed computing
  – Wireless as the last hop to the consumer
  – Internet of Things (where a thing may be a turbine shaft or a light bulb)
  – Spectrum sharing and re-use
An Environment for Transition

- Industry is welcome
  - Can buy the radios
  - Can get an FCC license to make their campus an experimental center
- Industry and venture can see ideas working on the testbed
  - They can also try their own ideas
  - They can license ideas they like and create products
  - Idea to product time tends to become shorter
- Many of these ideas that 5G and its successors see in their roadmaps
  - A chance to test drive in their full (2030) glory
More About Transition

• Keep in mind that we’re giving the radios to our best engineers and computer scientists

• As they graduate into the world, two things are likely
  – First, they’re going to want that high quality wireless experience at their workplace (gentle pressure for industry to join the party)
  – Second, they’ll have the right experience to find transformative uses for wireless communications
Education and Outreach

• Good testbeds lead educators to create courses for their students to use them
  – What better than a first class wireless experimental environment on campus to enable next generation wireless courses?
  – Experience with GENI suggests the testbed operator should also do some educational programs

• Straightforward to bring in undergraduates
  – Probably can arrange for some high schools to participate

• Outreach to scientific fields and underserved communities (e.g. EPSCOR schools)
HOW WE MAKE THIS HAPPEN
(aka the details)
Give students a $2000-$2500 radio that contains a mix of features that will cost $200 in 15 years. Ensure the features make the radio so good the students will use it in preference to built-in WIFI on their devices.

- New radios every 3 years
  - Students who already have a radio will get a new one
- Features selected by an advisory committee
  - After first release, we expect many features to be developed and tested on the existing radio
- Ability to replace modules
- We will likely have to design and build these radios
  - There’s community expertise (U. Colorado and Ettus) we can tap
A Possible First Radio

- Tablet sized with USB-3 connector (5Gbps full duplex)
- Three tunable antennas (100MHz to 6 GHz in 2MHz channels)
- An antenna with logic to deliver multiple 2Gbps data channels in the S-band
- Large FPGA and GPP and MIMO support
- Control system to lock/unlock access to full spectrum

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What’s This About A Lock?

• FCC 5.301-311 requires we have basic controls
  – A “Stop Buzzer” POC who can stop transmissions
  – Furthermore, should we find some frequencies interfere with critical services on a campus, need a way to ensure those frequencies are not used
  – Need to constrain accidental use outside campus (aka the experimental zone)
• Base stations will hand out tokens that unlock the spectrum
  – Good for 30 minutes; otherwise the radio simply operates in unlicensed bands
  – In return for token, radio reports bands most recently used (so we can investigate interference claims)
• Note: radios always locked out of key safety and GPS bands
Base Station

- Platforms that can run the same software as handsets
- Run multiple distinct protocols at a time (aka multiple experiments)
- Will have to manage deconfliction etc.
- Also manages permissions to devices to use spectrum experimentally

- Current plan is the base stations will be centrally managed (over the ‘Net)
- This allows one phone number, nationwide, for “Stop Buzzer
  - Consistently tracking of interference issues across all campuses
  - Spares campuses from 7x24 support and tracking
- Does not mean centralized capture of user data or central approval of experiments!
Radio Software

- Communal software that creates an agile software radio
  - Able to change frequencies quickly
  - Able to change protocols quickly
  - Able to run multiple protocols/frequencies concurrently

- Standard version (think Github) updated continuously with major release every 6 months
  - Advisory committee to select best new software to include
  - Releases so that courses/instructors can develop course around a specific (stable) release

- Makes the radio look like an IEEE 802 device (with enhancements) to other side of USB

- Mix of Public and Project License software (more on this later)
Intellectual Property

- Use an approach that has worked well in GENI
- Choice of two licenses:
  - Public: anyone can use the stuff you contribute provided they include your copyright notice
  - Project License: anyone can use the stuff you contribute within the testbed efforts, but other uses require another license.
- Goal is to make it easy to contribute your research and easy for others to use in their research
- GENI found about 2/3’s chose Public license and 1/3 Project License
FREQUENT QUESTIONS
How Big Will The Testbed Be?

- There are about 270 degree granting institutions
  - >250 have high speed Internet connectivity
  - Figure we will get 200 or more
- Numbers vary, but apparently between 7,000 to 10,000 Computer Science PhD students, with about 2,000 graduating each year
- The number of Electrical Engineering PhD students is comparable
- Figure 600+ base stations and 20,000+ radios at 200+ experimental campuses across all 50 states
  - Entire range of environments from urban to rural
  - Industry may add more

Sources: 2014 Taulbee Survey; NSF NCSES. The statistics generally track degrees awarded and new students accepted but not the current population.
Isn’t Industry Doing This?

• Christensen – Innovator’s Dilemma
  – The impact of many of these technologies on existing business models is unclear
  – Industry has difficulty with innovations whose results might threaten their business model

• What about 5G?
  – Many of the innovations here are listed in 5G’s plan
  – Much of that plan is about possibilities; 5G will refine itself as the planning progresses; attempts to accelerate 5G rollout will reduce what it includes
  – Our goal is push on possibilities and take capabilities well beyond 5G’s goals
What Would This Cost

• The thought is we would have an initial (3 year) phase to shake out the radio production process and software
  – Modest set of universities (c. 10)
  – Smaller user base (c. 100)
  – Perhaps two industry partners

• Full availability in years 4 through 7
  – New radio improved from initial phase in year 5
  – 200 universities
  – 20,000 students
  – Anyone else who wants to join in
Cost – 3 Year Initial Phase [c. $22M]

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<thead>
<tr>
<th>Item</th>
<th>Basis of Estimate</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio Software R1</td>
<td>First release may be from scratch</td>
<td>$7M</td>
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<tr>
<td>Radio Software R2 (partial)</td>
<td>largely integrate community improvements plus robustness</td>
<td>$1.5M</td>
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<tr>
<td>Radio Hardware R1 - handsets</td>
<td>250 radios (200 plus spares) x $2.5K; plus $3M design costs</td>
<td>$3.6M</td>
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<tr>
<td>Radio Hardware R1 – base stations</td>
<td>44 basestations (incl. spares) x $15K</td>
<td>$0.7M</td>
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<tr>
<td>Operations after 1st release (1.5 years)</td>
<td>24x7x365 is expensive; then there’s refresh/tech support; software hub support; $6M/year?</td>
<td>$9M</td>
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</table>

- 1 software and radio release at c. 18 months
Costs Years 4- 7 [c. $100M]

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<tr>
<th>Item</th>
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<th>Cost</th>
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</thead>
<tbody>
<tr>
<td>Radio Software R2 (completion)</td>
<td>Later releases largely integrate community improvements plus robustness</td>
<td>$1.5M</td>
</tr>
<tr>
<td>Radio Software R3</td>
<td>Later releases largely integrate community improvements plus robustness</td>
<td>$3M</td>
</tr>
<tr>
<td>Radio Software R4</td>
<td>Later releases largely integrate community improvements plus robustness</td>
<td>$3M</td>
</tr>
<tr>
<td>Radio Hardware R2 - handsets</td>
<td>22K radios (20K plus spares) x $2.5K; plus $2M design costs</td>
<td>$57M</td>
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<tr>
<td>Radio Hardware R2 – base stations</td>
<td>650 basestations (incl. spares) x $15K</td>
<td>$10M</td>
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<td>Operations (4 years)</td>
<td>24x7x365 is expensive; then there’s refresh/tech support; software hub support; $6M/year?</td>
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Isn’t GNU Radio/SCA Doing This?

- Both GNU Radio and the Software Communication Architecture (SCA) have contributed to the maturing of Software Radios

- However
  - They were designed in a different era with different expectations (e.g. SCA’s use of CORBA, GNU Radio’s struggle [now resolved] to support 802.11)
  - They don’t have the right licenses to enable a mix of open research and commercial transition

- So we can, and should, benefit from what they’ve achieved but we need to move forward
How Does Internet of Things (IOT) Fit?

The focus of this effort is on a radio that you’d have in your phone, tablet or laptop

The IoT is about networking **Things**

• The radios here are likely the way we talk to the “Things”
• Also some “Things” are likely to leverage the technologies tested here
  - Light bulbs that announce when they are reaching the end of their useful life: that’s probably a 50-cent radio. It will do WiFi.
    • So less capable than this radio, but a radio we want to talk to
  - A jet turbine shaft that announces when it is reaching the end of its useful life: that radio’s pricing is in the target range for this project.
    • Some details of the radio may differ due to embedded nature
Risks

• Launch risks
  – Getting the first radios working
    • always a challenge
  – Getting the software “right enough”
  – Both are reasons for a staged roll out

• Making sure the radios are desirable
  – If people don’t use them, we’ve failed
  – Packaging tradeoffs in radio
    • Concerns tablet sized radio will feel “large” vs.
    • Making radio possible to modify in the field