Upper Midband Software Defined Radio Workshop Report

September 11, 2023
Railway Exchange Building
Chicago, IL

Bertrand Hochwald and Jonathan Chisum (University of Notre Dame)
Ashutosh Sabharwal (Rice University)

Executive Summary

Motivation for the workshop: The Upper Midband Software-Defined Radio (SDR) Workshop on September 11, 2023 in Chicago, IL, provided a forum for the discussion of what the next generation of software defined radios should be to appeal to prototypers and researchers in wireless communication techniques for the 7-24 GHz bands (portions of the X, Ku, and K bands, collectively referred to as FR3). We invited experts in modeling, system & software design, use cases, and radio-frequency hardware and techniques to develop a vision for the SDR in these bands and help us shape a platform that could be a useful research tool. This workshop report summarizes the main points of discussion and conclusions.

Sponsorship: This workshop was sponsored by the National Science Foundation and the Office of the Undersecretary of Defense for Research and Engineering.

Participation: The participants, listed in Appendix I, were by invitation and represented a cross section of industry, government, and academic institutions. The one-day workshop was on September 11, 2023, in Chicago, IL. The participants were divided into three broadly-defined groups: 1) Use cases; 2) Systems and Software; 3) Hardware, according to their areas of specialty. The workshop began with three keynotes and proceeded to lightning talks around use cases for the SDR intended to drive deeper discussions later in the day. The three groups then separately discussed issues that were deemed important within their respective areas.

Observations and Conclusions

- **Aim Higher:** There was near-universal consensus that software defined radios (SDRs) and platforms developed for the lower bands (generally sub-6 GHz) lagged industry developments for these bands and hence were of limited use beyond research and propagation studies and commercial development of wireless communication systems. There is an opportunity for the design and development of upper midband SDR platforms that lead industry and defense organizations into new research directions, new commercial opportunities and are designed to accelerate innovation in the wireless industry.
- **Keynotes:** The keynote presentations detailed the importance of effective technological and policy advancements in the use of the FR3 band over the next ten years towards keeping the U.S. at the forefront of commercial and government wireless communication and radar systems. Indeed, the acknowledgment that the FR3 band, while reasonably large, will likely be shared since it has many incumbents. Hence, there is room for innovation in sharing and coexistence in the commercial world, and dominance in the defense world.
- **Use cases:** Use cases for the SDRs were varied but primarily divided into: **(i)** passive sensor platforms to enable spectrum monitoring and sharing; **(ii)** active sensing platforms for channel sounding and propagation studies; **(iii)** communication platforms for designing transmission and reception strategies; **(iv)** combined communication and radar platforms to study coexistence. Most use cases involved multiple radio-frequency chains, and the possibility of combined communication and radar coexistence was deemed a particular feature that should be supported in an SDR for the FR3 band. Some key recommendations included:

  - Simplified access to test spectrum (such as via experimental licenses) that allows over-the-air testing in the FR3 band.
  - Access to a testbed that allows a unified set of conditions for operating a wireless network, especially in a "no-consequences shared environment," where all stakeholders can measure the tested results of sharing methods.
  - Development of an open-source software environment compatible with Open RAN (O-RAN), and a unified programming environment (such as via Python) so that software can be exchanged without extensive compatibility issues.
  - Development of FPGA (field-programmable gate array) toolchains that allow high-speed data handling commensurate with the high bandwidths that are expected at these frequencies.
  - Flexible architecture through reconfigurable front-ends for small numbers of high-resolution, or large numbers of low-resolution Tx/Rx chains.
- **Systems and Software:** The importance of "plug-and-play" and ease of use were considered paramount for allowing users with various levels of expertise to immerse themselves in the use of the SDRs. Ideally, a user should be required to have familiarity with no more than a single language (such as Python) to perform even real-time functions. Past experience with SDR platforms has shown that their software ages quickly and their difficulty of use discourages maintaining and updating the platform. Key recommendations from the breakout:
  - Systems should be frequency-agile and support simultaneous monitoring of large bandwidth for spectrum management and sensing in the presence of incumbents.
  - System design should natively support AI/ML across the stack, ranging from hardware to whole network management.
  - Systems designs should natively support both the needs of communications and innovative sensing applications.
  - The designs should be scalable to support many antennas across the whole spectrum.
  - Software stacks to be stable, well-documented, and have extensive training resources, combined with expert support.
- **Hardware:** Cost, size, and power consumption were considered to be important factors, but most important was the ability to easily scale from few to many transceiver chains, especially in light of the need to overcome pathloss at the upper end of the FR3 band. Hence, modularity, and ease of use were considered fundamental. There was an acknowledgment that much of the ability to lower cost to ~$10K and power to 10's of Watts was dependent on the development of chipsets by commercial vendors in quantity. Just as important was the need to have extensive baseband processing capability to handle the transmitter and receiver functions that were likely to involve multiple radiofrequency chains. There was a universal recommendation that an early hardware offering was essential to ensure the research community is ahead of industry and standards bodies working in the FR3 band. This early solution will likely be something basic, such as block converters for use with existing wideband sub-6 GHz SDRs. Key recommendations from this breakout:
  - An early solution is necessary for researchers to inform the rapid development expected from industry. This basic solution may be based on extending existing sub-6-GHz SDRs.

    - Modularity with scalable numbers of transceivers is essential in the upper midband to balance cost and power consumption while supporting various applications ranging from single-directional antennas to MIMO and beamforming applications.
    - Modularity within a transceiver is also necessary to support upgrades in baseband, analog and RF/antenna domains. This requires well-defined baseband and analog antenna interfaces.
    - Baseband processing of multiple transceiver chains requires synchronization methods including daisy-chained or even over-the-air time references.

The report is organized as follows: first, the Keynotes are summarized. Then, the Breakout Sessions are presented in detail. The Appendices contain the list of participants, workshop agenda, and a link to the "Lightning Talks" that were used at the beginning of the workshop to motivate the breakout sessions.

Keynote Addresses

Keynote 1: Thyaga Nandagopal (NSF)

Speakers: Sudharman Jayaweera and Thyaga Nandagopal, National Science Foundation, Program Director and Division Director, respectively, for the Division of Innovation and Technology Ecosystems (ITE).

Summary: Sudharman Jayaweera introduced the TIP directorate, and then Dr. Nandagopal cast the NSF vision to anticipate SDR needs in 6-24 GHz bands. TIP wants to spur innovation, which requires both *SDRs* and *testbeds.* One of the major limitations of historical SDRs is that you can realize a future, but you cannot push the limits because you require custom front-ends or baseband solutions (e.g., processing power).

Some initial suggestions regarding what is needed for future 6-24 GHz SDRs included:

- End-to-end toolchains with small learning curves;
- Hardware for carrier-grade functionality (high Tx power, better filter choices);
- Diverse ecosystem is okay if we can cover the band with better performance;
- Frequency agile front-ends (willing to sacrifice some BW for filter performance);
- Open-source libraries with verifiable provenance;
- MMW bands are too hard (even for carrier radios), so let's look at 6-24 GHz.

The role of NSF & TIP:

- NSF and OUSD have common interest;
- Fund large-scale testbeds;
- Make the agility of the SDR commercial grade;
- Need an ecosystem;
- TIP cares about tech transfer–not just academic; needs to find its way into deployment.

Keynote 2: Monisha Ghosh (University of Notre Dame)

Speaker: Monisha Ghosh, Professor of Electrical Engineering, University of Notre Dame.

Summary: FR3 has already been named (7.125-24 GHz). Now is the time to find an SDR solution for these bands to inform spectrum policy and standards. The FR3 band comprises:

- Low-band (<1 GHz) characterized by very distinct propagation;
- Mid-band from 1-6 GHz, but shifting to 7-24 GHz;
- High-band (>24 GHz): so-far, sparsely deployed because performance has not yet met the promise, there is almost no indoor/outdoor propagation, base-station (BS) coverage is limited to half-a-block, and handset power is an issue;.
- Unlicensed: 5.925-7.125 GHz (share with FMB);
- New spectrum being considered: 12.2-12.7 GHz, 12.7-13.25 GHz (shared with satellite).

Looking back to 4G/5G, many of the improvements ended up being 10x more data. And yet almost none of the stated objectives have been met. This suggests that perhaps 6G should not just multiply data rates by 10. The good news from 4G and 5G networks is that the user experience data rates were realistic and are being met. In addition, given the incumbency in the FR3 band, "**anything we do in the upper midband with SDRs must address the reality of shared spectrum.**" The implications for 6G are that the user experience data rates should be realistic instead of aspirational, and 6G should inherently address shared spectrum.

A summary of the FCC TAC regarding 7.125-24 GHz was provided. From January, 2022 to August, 2023 they performed a spectrum inventory that went beyond allocations. They discussed types of sharing options: unlicensed sharing (listen before talk) or database (not dynamic) and whether new spectrum should be licensed, unlicensed, or a combination of the two. It was suggested that perhaps we need to re-examine cognitive radios and dynamic spectrum access (DSA).

Future spectrum requirements: There is a consensus that terrestrial wireless 6G requires 2 GHz of spectrum by 2030. The 7.125-15 GHz band is preferred over 15-24 GHz due to challenges at higher frequencies. For non-terrestrial, existing allocations in 7.125-24 GHz must be protected because their use continues to grow. It is clear that finding 2 GHz of unallocated spectrum in these bands cannot be achieved by moving incumbents, so you will have to share.

Sharing vs. coexistence: Sharing is between "unlike" systems and examples include TV white spaces, CBRS, C-band/Radar Altimeters. In shared systems the figure of merit (FoM) is RF-only: the interference-to-noise ratio. Coexistence is between "like systems," such as WiFi/WiFi, WiFi/LAA, WiFi/5GNRU, and private 5G. In coexisting systems the FoM is at both RF and MAC layers.

Key Takeaways:

- 7.125-8.5 GHz: pretty much fully allocated - sharing is already happening;
- 8.5-13.75 GHz: may be available for sharing with limited restrictions, 2500 Mhz (10.7-13.25) allocated for non-federal use (12.2-13.25 already under consideration from FCC);
- 17.1-24 GHz: lots of satellites, 2200 MHz (17.8-18.6, and 18.8-20.2) may be practical for coexistence if use of earth stations. 17.7-17.8 GHz is not allocated for federal use.

TAC Recommendations:

- 7.125-8.5: lowest, easiest to use, better propagation;
- 10.7-13.25: sharing with non-federal satellites;
- 14-14.2: sharing with space research;
- 17.8-18.6, 18.8-20.2: sharing with federal satellite – additional analysis needed with regard to commercial satellite use of this part of the spectrum.

In the 12 GHz band:

- FCC denied allocating 12.2-12.7 GHz to terrestrial mobile due to concerns with satcom DL;
- Sharing with high-power mobile outdoor is hardest application;
- 12.7-13.25: permits high-power terrestrial mobile shared with satellite UL–future 6G band?

- Need to consider adjacent channel interference.

Research issues in the 7.125-24 GHz band:
- Propagation: terrestrial for MIMO has largely been unstudied; indoor;
- Interference studies: sharing necessary, MIMO DoF should be "spend" on sharing with incumbents. Co-channel interference;
- Spectrum measurement.

Closing Thoughts:
- New metrics: 10x is not sustainable; power consumption is an increasingly important metric;
- 80% data usage is indoor, outdoor high-power BS is not green approach to servicing this;
- Connect everyone: should be looking in 7-24 GHz for this, not sub-THz;
- Design and architecture of 6G: ability to operate seamlessly in all types of spectrum including licensed, shared, and unlicensed–**6G should be sharing native**.

Q&A:
- Thyaga: Satcomm: need to be dynamic? Agree. SDRs should be dynamically changeable since FCC may change the allocation.
- Thyaga: Economics: 12 GHz experimental licenses; on the satellite side - lost expertise
    - Sundeep: companies in wireless collaborate well with Universities, but space-comms don't collaborate well with academics; (Monisha) They are all proprietary systems → so much of sharing in this band is with satellite so transparency is important.
- Bert: licensed/unlicensed, shared/unshared:
    - Licensed, unshared: allows for CAPEX.
    - Licensed, shared: CBRS (in U.S.), Locally-licensed spectrum (Europe).
    - 5G private has been very positive, even if operators revenue is declining.
    - The cellular approach to sharing is very immature; it is not part of the 3GPP stack to share →need to share natively in 6G 3GPP.
    - Do you want 100 MHz of exclusive, licensed spectrum or 500 MHz of shared?
- Army perspective:
    - Most important is frequency agility and wideband/tunable antennas and tunable filters cannot serve them all so hardware requires modularity.
    - (Monisha) 4G: carrier aggregation has been very successful – very important for non-contiguous spectrum.

Keynote 3: Tom Rondeau (OUSD R&E)

Speaker: Tom Rondeau, Principal Director for FutureG & 5G for the U.S. Department of Defense, Office of the Undersecretary of Defense for Research and Engineering (OUSD(R&E)). No slides were presented.

Summary: By way of background, much of the work of the FutureG efforts are based on core technologies developed over the past decades through offices such DARPA MTO, applied in systems in offices like DARPA STO, and now being applied and transitioned in FutureG Wireless networks.

Dr. Rondeau commented that 5G was a great technology push but echoed Prof. Ghosh's suggestion that there was no essential reason for the "10x pushes"; however, it did revolutionize infrastructure: SDNs are real now. 6G will be about maturing these, especially the software defined nature. This is because while technology tends to advance in 10 year cycles, markets follow in 20 year cycles.

In 6G networks we must consider security. There is a different valuation of networks: data is personal revealing our behavior and identity so we must ask, "How can we value security in networking systems?" For example, with both the frequencies and the bandwidths in FR3, it becomes possible to perform integrated communications and high-performance (e.g, high-spatial-resolution) sensing. It is not a coincidence that there are many incumbent radar systems in the C-/X-band! 6G should be designed as open, transparent, secure, and resilient.

In the FutureG effort, 5G is being transitioned to DoD CIO with four main thrusts:

1. Dual Use/Purpose and industrial influence: tech with commercial and DoD value → as soon as industry figures out how to monetize, they quickly overtake government capabilities.
2. Instant and Ubiquitous: operational tennants, good connectivity for everyone in the world. How to utilize existing commercial infrastructure to help us? Data goes over the internet, etc. How can we secure data over the global information infrastructure? Includes space (non-terrestrial).
3. Expeditionary and Tactical Communications: While the first two thrusts target the "gray zones", as we move into contested areas we need EM signature control.
4. Integrated sensing and communications: As stated before, in bands that are suitable for sensing, dual-use becomes compelling.

There are many use cases that need to be investigated in realistic testbeds. Two examples were discussed: the National Radio Dynamic Zone (NRDZ) and Playas New Mexico, an abandoned town setup with a flexible cellular infrastructure and spectrum sensing across the town. It is open to research (more so than a U.S. military facility) and is suitable for investigating questions, like how to maneuver in this environment (from a DoD perspective) when under threat of sensors, comms, and cyber in future RF systems.

DoD perspective on spectrum sharing: new FR3 bands have a lot of DoD assets including fire-control, missile defense, and satcom. The lower bands provide a wider field-of-view (FoV), while the upper (e.g., X-band) have narrower FoV (e.g., fire control). It was noted that frequency is critical to radar. When we talk about military radar and moving bands, you are talking about changing physics. Therefore, the solution for sharing spectrum is going to be based on the physics and the policy in those bands. CBRS is a specific approach to sharing that works with that specific radar system, but if you change any parameters you arrive at a new sharing solution. The 12.2-13.25 GHz band does not have any current DoD concerns, but moving outside these bands will be a "fight". In a sharing context, it must be considered that there are incredible phased-array systems with exquisite SLL(sidelobe)/nulling features, which change how you interact with those systems. They "look" with a specific pattern, and their propagation is different; all of which matters in a sharing system. While there has been a lot of work on propagation in these bands, there is a need to motivate the DSA community to investigate these problems.

Hardware: there is a need for cost-effective and available hardware in order to do large scale propagation measurements. Hardware should provide fast maneuverability, such as fast switching times (dual use–fast-frequency hopping (FFH) radar), and it must include good filtering. It was noted that dual-use (comms/radar) SDRs have specific demands (beyond comms applications) to support the radar missions, including very low phase noise, fast frequency agility, high processing power close to the RF, and low-latency control. All aspects are needed not only for processing but also for coexistence. Some of the hardware features could be considered in O-RAN including filtering technologies, phase coherent systems, and security–can facilities instrument/monitor for better security. Even if O-RAN is not inherently more secure, the fact that it is open lends itself to scrutiny and analysis. It was noted that some hardware development will be enabled through CHIPs act including the Microelectronics (ME) Commons hubs (regional structures) which will provide tools and fabrication facilities in key tech areas for 5G/6G. This will provide more technology for sharing/coexistence and enable more cost-effective access to FR3 bands.

Q&A:

- Laneman: Hypersonics - new opportunities to rethink sharing;
- SENSR: DoD, NOAA, etc. program - reimagine ATC radar system - modernize and make it better as a protection system in addition to weather and air traffic;
- Sharing with Radar concern: the increasing ability to sense radar systems (RWS in commercial equipment) - how can you deploy these systems but protect this information? There is a community of privacy-enhancing technologies that could be brought to bear on protecting this kind of fingerprint.

Breakout Session I: Use Cases

Participants: Martin Doczkat (FCC), Rahman Doost-Mohammady (Rice), Bert Hochwald (Notre Dame), Amr-Haj Omar (National Instruments), Neel Pandeya (National Instruments), Monish Ghosh (Notre Dame), Scott Fox (OUSD), Bruce Mueller (Motorola Soln's), Ziv Nuss (Sensorz), Erik Luther (Saleae), Cliff Ellement (ThinkRF), Nada Golmie (NIST), Dinesh Bharadia (UCSD), Kobus van der Merwe (Utah)
Session Leads: Dinesh Bharadia (lead) and Kobus Van der Merwe (co-lead)
Graduate Student Scribe: Chris Wahl (Notre Dame)

We started by articulating the need to consider the broader "ecosystem" to enable upper midband related research. This is followed by a description of the use cases identified during the session. The section ends with detailed requirements that will need to be satisfied to enable upper midband research and use case exploration.

Executive Summary

The need for an upper midband "ecosystem": A key takeaway from this breakout discussion is that use cases encompass a "broad ecosystem" needed to enable and accelerate research related to the exploration and use of upper midband spectrum (FR3). That is, while appropriate SDR technology capable of operating in FR3 is critical for any use case exploration, it is "just" a component and several other components that are also critical for impactful research. Specifically, other components critical to this ecosystem include:

1. **Spectrum access**: Access to spectrum that can be used for experimentation is absolutely critical to enable research related to FR3;
2. **Real world testbeds**: Similarly, being able to use FR3 spectrum in a real world testbed environment will be critical to enable impactful research; (The importance of enabling over-the-air experimentation was also emphasized by keynote speaker Tom Rondeau.)
3. **Open source domain specific software**: Well supported open source domain specific software, e.g., 5G and beyond, O-RAN, etc., compatible with FR3 SDR equipment, is critical to enable and accelerate research effort.
4. **Sophisticated toolchain development workflows**: There is an expectation that FR3 research will require sophisticated FPGA toolchains. Access to high quality open source, and/or commercial FPGA building blocks and toolchains will be needed.

A key recommendation then, for future funding opportunities, is to ensure that all aspects of this broader ecosystem are addressed. This might, for example, include establishing procedures and mechanisms with regulatory agencies to ensure appropriate spectrum access and structuring funding opportunities to allow the participation/contribution of appropriate open source communities and commercial toolchain vendors.

Upper Midband Use Cases

The breakout session identified four general categories of use cases, with related and overlapping specific use case examples within each category:

1. **Passive sensing and detection (receive only):** Passive sensing and detection represent a fundamental building block/enabler for the use of FR3 spectrum. Specific examples include the creation of FR3 specific digital spectrum twin capabilities, detecting, localizing, and classifying RF signals, “intent of signal” classification (i.e., distinguishing between intentional and unintentional interference), 3D sensing that covers both terrestrial and non-terrestrial transmissions, RF anomaly detection (e.g., identifying unauthorized interference, spoofing and interloper detection, distinguishing between intentional interference and co-channel noise etc.), detecting radar signals, and the ability to decode transmitted signals.
2. **Active sensing and detection (receive and transmit):** Active sensing and detection similarly represent a fundamental capability to characterize RF systems and their interaction with the radio channel. A classic, but enduring, example is RF propagation analysis, a critical component of developing accurate propagation models which is widely used in spectrum planning, interference prediction, and spectrum sharing. While passive sensing and detection use cases ultimately aim to be “receive only”, *research* related to passive sensing and detection might in fact require receive and transmit capabilities, suggesting an overlap between the research objectives/needs of these use case categories.
3. **Communication (receive and transmit):** Communication research related to FR3 will remain a key use case and research focus. Communication scenarios will include terrestrial and non-terrestrial communication, different duplexing modalities (FDD, TDD and full duplex), and will specifically include the need for more efficient use of spectrum, the ability to share spectrum, and the ability to communicate in non-ideal RF conditions. Ever increasing “spectrum congestion” also suggests the need to revisit cognitive radio approaches, possibly combined with new software defined architectures and abstractions. Since it occupies the “upper midband”, FR3 will also require exploration of communication technologies related to beamforming and beam steering, MIMO and massive MIMO, adaptable RF frontends and antenna systems, etc. Finally, the applicability of O-RAN principles and abstractions to the FR3 domain remain an open question.
4. **Combined communication and sensing (receive and transmit):** A key emerging use case category, particularly relevant to FR3, involves the combining of communication and sensing into an integrated system. Such an approach offers a multitude of potential benefits that need to be explored and experimented with. Examples include the ability to optimize the communication system based on detected obstructing objects, and using sensing to provide situational awareness to a communication system (e.g., using connected vehicle communication systems to also provide detection of pedestrians or other vehicles).

Functional Requirements

To enable multiple use cases and the following requirements should be met:

1. **Open-Sense Framework (O-RAN-like):** Developing an open and flexible framework for sensing akin to O-RAN can provide the foundation for integrating different SDRs, sensors, and networks.

2. **Large Number of Sensors:** Use scalable and distributed sensor networks to cover a wide area efficiently.
3. **Multiple Networks:** Implement support for various wireless networks (e.g., Wi-Fi, cellular, satellite) within the SDR ecosystem.
4. **Propagation Models:** Develop tools and models for propagation analysis to understand how signals propagate in different environments.
5. **Beamforming/MIMO Prototyping:** Employ tools that enable beamforming and massive MIMO prototyping for advanced signal processing and antenna techniques.
6. **Wider Bandwidth:** Support wider bandwidth for both sensing and communication perspectives. Utilize direct sampling techniques when applicable to reduce analog components and enhance flexibility.
7. **Different SDRs with Different Front Ends:** Develop a flexible ecosystem that can accommodate SDRs with various front-end capabilities, including different frequency ranges.
8. **Aggregated Bandwidth:** Implement mechanisms to aggregate bandwidth from different parts of the spectrum to maximize data throughput.
9. **Reconfigurable ADCs:** Utilize reconfigurable analog-to-digital converters (ADCs) to adapt to different signal characteristics and bandwidths.
10. **Fast Data Offloading:** Consider high-speed data offloading mechanisms to transfer data from SDRs to processing units efficiently.
11. **O-RAN Compatibility:** Ensure compatibility with O-RAN principles and implementations for openness and interoperability.
12. **Dynamic Range:** Support multichannel operation and a wide dynamic range to handle diverse signal scenarios.
13. **Coexistence and Filtering:** Implement effective filtering mechanisms to manage coexistence with other networks and minimize interference.

Why do current solutions not meet the requirements?

The *de facto* solution is to use GNU Radio with software defined radios. There exist SDRs in the bands of interest; however, they lack a variety of attributes.

Drawbacks of USRPs (Universal Software Radio Peripherals) as a *de facto* solution: USRPs are devices that can interface with a computer to transmit and receive radio signals using software. However, USRPs have some limitations that may affect their suitability for some SDR applications.

1. **Frequency Range Limitations:** USRPs can only cover part of the frequency spectrum, especially in the sub-6 GHz range, which is also known as the mid-band. This can limit their usability for some applications that require higher frequencies, such as 5G and beyond, which use the FR3 band.
2. **Limited MIMO Capabilities:** To achieve MIMO, one needs to handle multiple USRPs at a massive scale, which can be challenging in terms of synchronization and coordination.
3. **Software-Heavy Implementation:** Developing applications for USRPs often requires significant software development, which can be resource-intensive and time-consuming. Some of the software tools that are commonly used for USRPs are GNU Radio, C++, and UHD (USRP

Hardware Driver). These tools may have different levels of complexity and compatibility, which can affect the ease of development and testing of SDR applications.

4. **Lack of Real-Time Use Cases:** USRPs may have limitations in handling real-time applications that demand low-latency processing.

For example, Signal Hound offers a wide-band SDR that covers 100 MHz to 43.5 GHz, which is suitable for many applications such as cellular, Wi-Fi, Bluetooth, radar, satellite communication, and more, covering FR3 and more. However, one limitation is that these radios do not support multiple-input multiple-output (MIMO) capabilities, which means that they cannot receive multiple data streams simultaneously using multiple antennas. Therefore, Signal Hound SDRs cannot generally be used for beamforming. A third limitation of Signal Hounds is that they do not offer many software tools for developing and testing SDR applications. Their software mainly includes Spike, a spectrum analyzer software, and the Signal Hound SDK, a software development kit for programming SDRs using C/C++ or Python. However, these tools are not sufficient for some advanced or specialized SDR applications that require more features or functionalities.

We need to develop an entire ecosystem with radio, MIMO capabilities, and tools that support heterogeneous computing with the following features:

1. **Usability:** User-friendly interfaces and ease of programmability are essential to make SDR technology accessible to a wider workforce.
2. **Software Adaptability and Reusability:** SDR software should be adaptable and reusable across different applications to reduce development time.
3. **Virtualization Support:** Ensure SDRs can be easily virtualized to run on cloud or edge computing platforms.
4. **Compiler Capabilities:** Evaluate the compiler capabilities of SDR devices to optimize performance and resource usage.
5. **Cost-Effectiveness:** Consider the cost implications of both hardware and software components to ensure affordability.
6. **Hardware Considerations:** Assess the quality of RF filters, active and passive filters, RF electronics, and RF ICs for signal processing and filtering capabilities.
7. **Scalability:** Ensure scalability in terms of gain, digital channels, and aperture size to meet evolving requirements.
8. **Receiver Sensitivity:** Evaluate receiver sensitivity across broadband frequencies, considering noise figure and dynamic range.
9. **Commercial Toolchains:** Utilize commercial SDR development toolchains that offer a wide range of features and support.
10. **Automatic Code Conversion:** Explore tools that can automatically convert code from languages like Python/C to FPGA code for efficient implementation.
11. **Open RAN/Open Sense:** Leverage open frameworks like O-RAN and Open Sense to build an ecosystem of SDRs and modular execution capabilities.
12. **Modularity and Compatibility:** Design SDR systems with modularity in mind, allowing different components to work together seamlessly and be compatible with O-RAN implementations.

13. **Deployability:** Consider deployment factors such as backhaul, power requirements, and robustness for various usage scenarios, including outdoor environments.
14. **Propagation Analysis Tools:** Use tools and simulations for propagation analysis to optimize system design based on the RF frequency.
15. **Plug and Play:** Aim for easy setup and zero-touch provisioning to reduce deployment complexity.
16. **Automation and Resource Management:** Implement automation for job handling and resource management, including lifecycle management of SDRs.
17. **API and Hooks:** Provide a user-friendly API that allows users to configure SDRs for different sensing tasks, energy sensing, and packet detection.

Breakout Session 2: System and Software Requirements

Participants: Ali Abedi (Stanford), Sundeep Rangan (NYU), David Kirkwood (FutureG), Chris Dick (Nvidia) Alex Wyglinski (WPI), Abhimanyu (Manu) Gosain (FutureG), Ashutosh Sabharwal (Rice), Tom Rondeau (OUSD), James Swindell (Army), Tomasso Melodia (Northeastern), Alhussein Abouzeid (NSF), Thyaga Nandagopal (NSF), Yasaman Ghasempour (Princeton), Srinivas Shakkottai (Texas A&M)
Session Leads: Yasaman Ghasempour (lead), Srinivas Shakkottai (co-lead)
Graduate Student Scribe: Xiangbo Meng (Notre Dame)

Executive Summary

Given that there are many potential use cases for midband spectrum, one challenge is to identify a comprehensive set of software and hardware requirements for the SDR. Through discussions, we have identified four key requirements for the system and software to support the diverse range of use cases:

1. The system should be frequency-agile and support simultaneous monitoring of a wide range of bandwidth while operating under power limits. This is essential for spectrum management and sensing as well as for bandwidth aggregation to support higher data rates. Equally importantly, the hardware should support sharp filtering to minimize out of band transmission, which is important for co-existence with satellite users.
2. The system should support the exploitation of ML/AL across the stack, from front-end, waveforms, to MAC protocols and above. All existing SDR systems were originally designed before the era of AI/ML; hence, applying AI-in-the-loop techniques have been an afterthought. Different from the past, it is important to take into account the flexibility needed for such data-driven protocols into the fabric of the SDR system, both in the data plane and control plane.
3. One major driver for FR3 bands is the integration of communication and sensing. The next-generation of SDR systems should allow for flexible and dynamic sharing of resources (antennas, compute power, etc) between communication and sensing. Furthermore, an unprecedented level of flexibility is needed for real-time sensing that motivates re-thinking hardware capabilities, e.g., the ability to change the waveforms in real-time has important applications in sensing (mostly in DoD settings) but cannot be realized with existing systems.
4. Given that the path loss in this regime is higher than sub-6 GHz band, flexible and hybrid multi-antenna arrays are required for dynamic beamforming and wavefront engineering. Wavefront engineering can indeed play a key role in mitigating the blockage in higher frequencies (closer to 24 GHz), near-field beam focusing and sensing, among others.

There was a unanimous consensus on the significance of software. A uniform and standardized software platform that can work with a variety of radios and compute systems can be transformational. The adoption of a universal software platform would also benefit workforce development, student training, and adoption in the classroom. The software should allow varying performance so that beginners can have a functioning radio, yet allow an expert user more functionality in data collection and visualization as needed. Ideally, the software should only involve a single, extensively-used language, such as Python. However, the real-time nature of communication applications implies that the stack might have to be written in lower level languages, with interfaces that can support Python.

Finally, the architecture of SDRs should be modular such that different components (front-end, baseband and compute, etc) can be independently configured, controlled, and upgraded. A modular radio system combines both the flexibility of software definition and the performance gains of specialized hardware. While the benefits and tradeoffs of using general-purpose vs. custom hardware is well investigated in other domains (for example ML), the performance and latency tradeoffs are not well understood for SDRs. The literature on modular architectures for SDRs is thin and much more investigation is needed in this space.

Lessons from the Past

What are the ingredients of a successful open-source software community? In general, it is not sufficient to simply post graduate-student-authored software projects on GitHub and expect uptake and development. A path to commercialization is critical, as it draws in professional users to contribute and manage open-source project development. A corporate sponsor is often key to ensuring longevity, professionalism and widespread uptake of open source software projects. Examples include those of Python being supported by Google, or Linux by Intel.

The question is whether these ingredients exist for software defined radio networks in the FR3 band? The general observation is that private 5G networks are taking off and such small scale deployments are ideal for rapidly adaptable software and systems, which might not be scalable to support millions of users at a commercial grade carrier. However, in spite of efforts such as srsRAN and OAI, no fully modular and universal solutions are available with a low barrier to entry for researchers to work with. Software communities need encouragement–-most importantly initially from the federal agencies, and subsequently from a corporate sponsor as applications become more widespread and paths to commercialization become lucrative.

Recommendation for Future Funding Initiatives

The upper midband FR3 spectrum has both the characteristics of the sub-six FR1 band at the low end of the spectrum, while having the properties closer to the mm-Wave FR2 band at the high end of the spectrum band. Much of the spectrum is occupied by existing stakeholders, and so sharing the spectrum for any active use cases is critical. Furthermore, given the interactions across applications, disaggregated radio stacks, and radio hardware, it is likely that simple model-based approaches will need to be augmented by data-driven AI approaches. Thus, the three major elements to consider for fundamental and applied research into software and systems are: (i) software architectures supporting adaptable end-to-end circuits and systems, (ii) systems for spectrum sharing and interference management, and (iii) Native AI-in-the-loop architecture in a disaggregated system stack. A focus on demonstrable use cases that can promote industry and societal uptake of developed architecture and systems will be crucial for success of research results beyond academic publications.

1. **Software for Circuits and Systems:** The success for FR3 will depend on a tight integration between the end-to-end system elements such as circuits, RF frontend, software defined radio and communication stack. Disaggregated software systems that can be easily modified in a modular manner will be important to ensure that community members can contribute advances at different levels and yet be able to validate their designs with complete over-the-air experiments. Support for equipment development/purchase and testing in emerging FR3 bands will be valuable.
2. **Spectrum Sharing Approaches:** The spectrum in the FR3 band is already occupied by legacy users such as satellite communication and a variety of DOD applications, including airborne radars. A sharing solution utilizing this band jointly for applications such as cellular communications will be critical. A specific question to consider is whether a spectrum access server in the manner of that used in CBRS will be viable, given the security implications of identifying whether an airborne radar is in use? Sharing of the satellite uplink bands might be possible in the short term, since terrestrial communication is unlikely to interfere much with receivers located at satellites. The lack of open source stacks for satellite communications implies studies on their coordination are currently very difficult.
3. **Native-AI in the Loop:** The complex cross-layer relationships between channel physics, hardware, software and applications imply that the FR3 cellular stack might benefit from AI-native algorithms, starting with PHY-MAC and rising up to management and control functions. These models would likely have to be pre-trained on an accurate systems emulator due to the risks associated with training in the real system deployment. ML models would need to be small and well structured to allow running them in real time. Ideas on meta-learning, contextual learning and transformers would be fruitful areas of study in the context of control of wireless systems.
4. **Applications and Adoption:** Interest from industry sponsors is likely to be low until clear use cases for the FR3 band emerge. Some of these applications could be on private NextG networks, utilized at locations such as ports and warehouses to promote efficient tracking and logistics, or in use cases, such as AR/VR gaming and collaboration. Hence, end-to-end validations and demonstrations with such use cases. Facilitating the collaboration between non-profit, startups, industry, DoD, and academia will enable such use cases to emerge naturally.

Breakout Session 3: Hardware Requirements

Participants: Taiyun Chi (Rice), Xinyu Zhang (UCSD), Jonathan Chisum (ND), Dan Pedtke (Notre Dame), Joshua Roy (GRA, ND), Steve Harry (AFRL), Aditya Dhananjay (PiRadio), Wyatt Taylor (Epiq Solutions), Sudharman Jayaweera (NSF), Matt Ettus (self), Marcus Miller (OUSD), Tod Schumann (NTIA), Dan Kuester (NIST), Jose Torres (MITRE),
Session Leads: Taiyun Chi (lead) and Xinyu Zhang (co-lead)
Graduate Student Scribe: Michale Baram

Executive Summary

Fourteen attendees from academia, industry, and government attended the hardware breakout session. The discussions were insightful, touching upon both current challenges and future possibilities for the upper midband spectrum. The discussions started with identifying hardware needs to support new use cases in the upper midband, which had been presented earlier during morning lightning talks.

1. **Requirements:** As noted in the use-cases report, there are a wide diversity of antenna requirements including single-element, few-element, phased arrays, and even distributed arrays. Therefore, one of the driving hardware requirement is scalability over channel count, so that multiple SDRs, including spatially non-collocated, can be scaled to support diverse upper midband use cases that would require just a few antennas in low-power wireless sensing applications to hundreds of antennas in massive MIMO. Additional hardware requirements including bandwidth, tunability, agility, baseband interface, SWaP-C, etc. are also discussed. Given the wide range of specifications for various use cases, the hardware should be compatible with the diverse demands of upper midband use cases but not overly designed. This motivated a modular approach to SDR hardware. A key observation is that routing SDR signals to/from antennas is much more challenging in the FR3 bands than in the FR1 bands. As such, care must be taken to minimize loss and maintain phase stability in the interconnection manifolds between electrically large SDR channels and the tightly-spaced (often half-wave-spaced) antenna elements.
2. **Early platform:** Next, we assessed the currently available hardware platforms and recognized the importance of having an early experimental platform to kick off research in the upper midband and lead its future development. In order for the research community to “get ahead" of, and therefore inform industry development, it is essential that an early upper midband SDR solution exists, even if it is not ideal and does not support all use cases. It was discussed that a likely initial offering would be block frequency converters to/from existing wideband sub-6 GHz SDRs – this would be similar to a low-cost version of the frequency converters used in millimeter-wave test equipment.
3. **Ideal platform:** After understanding the present landscape, the dialogue transitioned to what an “ideal” hardware platform would be. We brainstormed new hardware features on the circuit, antenna, packaging, and system levels, discussed their design challenges, and came up with potential research directions to overcome these challenges. As SDR hardware design involves

expertise in multiple domains, collaborations with experts in the software/firmware design and end users are critical to accelerate the development cycle.

Below are consolidated insights gathered from the discussions.

Hardware Requirements and Potential Solutions

To explore the projected 6G use cases and associated research challenges on the upper midband, the participants identified the following requirements for the upper midband SDR along with potential ways to meet the requirements.

1. **Scalability and Synchronization:** The diverse use cases in the upper midband range from low-power passive sensing, which requires only a few high-quality, high-resolution RF chains, to new MIMO paradigms such as Giga MIMO, which is the 6G-version of massive MIMO and would require hundreds to thousands of elements requiring lower quality and fewer number of bits. Thus, the SDR hardware architecture has to be scalable. The key to achieving such scalability is to have modularized RF front-end and antenna designs, while ensuring the footprint of each element is smaller than $\lambda/2 \times \lambda/2$. Fan-in and fan-out manifolds could prove useful in mapping from SDRs to antenna array pitch.

   Additionally, support for MIMO necessarily entails tight synchronization across all RF chains, including not just shared baseband modules, but also shared sampling clock (for sampling time synchronization) and LO (for carrier frequency and phase synchronization). Routing high-frequency clocks and LO signals over a large number of RF chains is a non-trivial challenge. This complexity grows further with recent developments in distributed MIMOs, which have shown significant performance improvement in communication and sensing. As such new methods for large-scale synchronization (including daisy-chaining and broadcast methods) are needed.

   Baseband processing and data converters for massive (and Giga) MIMO systems are a power and complexity bottleneck. It was proposed that perhaps channel count and effective number of bits could be dynamic: for example, a fixed 64-bit baseband interface could support either 16-bit data converters for a small 4-antenna MIMO transmitter, or it could support 4-bit data converters for a 16-antenna MIMO transmitter. This would help to manage baseband complexity and increase processing speed in highly scaled systems. This flexibility could be dynamically provided at the circuit level or it could be realized through a wide array of daughter-cards.

2. **Bandwidth, Tunability, and Spectrum Agility:** The spectrum policy on the upper midband is yet to be formulated. However, it may share similarities to those mature spectrum bands involving similar spectrum sharing issues (e.g., the CBRS band). The upper midband spectrum available for 6G use will likely be fragmented scattering across the 7-24 GHz range. Therefore, the SDR should ideally support aggregation or disaggregated use of these diverse fragments. It is interesting to note that despite the diverse use cases in the upper midband, the consensus from the workshop indicated that ~1 GHz of instantaneous bandwidth would likely be sufficient for most

upper midband applications. This bandwidth can be readily supported by today’s data converters (ADCs and DACs) and baseband processors such as RFSoC.

When transitioning into the RF frontend design, having a single piece of RF frontend to support up to all available spectra across 7-24 GHz can be challenging, albeit providing the ideal flexibility. One simple workaround is to aggregate multiple pieces of RF frontends, each supporting one or multiple adjacent spectrum fragments. Of course, the SDR itself should possess high spectrum agility to quickly switch across these fragments for spectrum sensing or communication.

3. **Baseband Interface:** For the baseband interface, high-end FPGAs with a high sampling rate, such as the RFSoC, were identified as preferred options. Many of the state-of-the-art sub-6 GHz software radio platforms are using RFSoC. Leveraging pre-existing baseband hardware along with the firmware/drivers can expedite development timelines and enhance cost efficiency.
4. **Antennas:** To scale toward Giga MIMO, the upper midband antennas are likely to continue adopting the 5G hybrid-beamforming architecture, consisting of many RF chains, each connecting to a phased array. Accordingly, the SDR platform should be equipped with an “array of subarrays" antenna architecture. The phased array (subarray) should be modularized to enable easy scalability. For the higher spectrum of the upper midband, given the small antenna pitch size (e.g., λ/2 is only ~0.6 cm at 24 GHz), the antennas within each subarray need to be co-packaged with a multi-channel RF frontend, so that only a baseband interface (or IF lying in the sub-6 GHz band) is exposed to facilitate system integration. On the other hand, for the lower spectrum of the upper midband, designs can probably reuse the relatively matured architecture in the sub-6GHz.
5. **Modularized Hardware:** It was noted that the pace of innovation for baseband ICs is faster than mixed-signal ICs (data converters) and RF ICs and therefore it is important to use, as much as possible, standard interfaces between these layers. These interfaces may be chip-to-chip interfaces (e.g., JESD204 data-converter interfaces), board-to-board (e.g., FMC), or even connector-to-connector. For example, many sub-6 GHz SDRs use the common SMA connector which has made pairing commercially available antennas from separate vendors with SDRs. However, as frequencies increase and the number of antenna ports goes up, SMA connectors cannot always fit on λ/2-pitch. Alternatives exist including the SMP connector but whichever connector is used should be standardized to support mix-and-match antenna modules with SDRs.
6. **Size, weight, power, and cost (SWaP-C):** The SDR platform should ideally possess a low SWaP (size, weight, power consumption, and cost), or at least be able to scale down to a low SWaP to accommodate use cases such as low-power IoT and drone networks. For such use cases, high-SWaP-C baseband processors such as the RFSoC may not be suitable. Instead, general processors (e.g., ARM or Intel) are desirable alternatives. Cost was also identified as a key factor for academic research. The NI USRP has proven to be a benchmark of affordability, to enable wide adoption by researchers in the wireless communication and networking area. Yet high-end baseband processors, high-frequency RF front-ends, and a large number of RF modules combined together may significantly elevate the cost of upper midband SDRs.
7. ***Other requirements:*** To explore coexistence between radio and radar on the upper midband, the SDR itself will need to have a high dynamic range, commensurate with radar devices. In addition, the SDR should be easily programmable for exploring other unique challenges for upper midband, such as coexistence between directional transmitters and directional spectrum sensing.

Available SDRs or Hardware Modules for Upper Midband

Full-fledged SDRs:

- **ADI** recently introduced an X-band (8-12 GHz) evaluation platform (https://www.analog.com/en/design-center/evaluation-hardware-and-software/evaluation-boards-kits/x-band-development-platform.html#eb-overview), which incorporates RFSoC-based FPGA baseband processor, frequency converter, beamformer, along with an array of subarrays antenna. The ADI platform supports up to 4 RF chains and 32 antenna elements.
- **piRadio** is developing a similar SDR, aiming to support the 7-24 GHz spectrum along with 8x8 MIMO.
- **Intel** recently released an extremely wideband RF sampling FPGA platform (https://www.intel.com/content/www/us/en/architecture-and-technology/programmable/analog-rf-fpga.html), which promises to achieve 64 Gsps, potentially enabling direct RF sampling for the upper midband.

Yet, none of these platforms is readily available as of today, especially at a low-SWaP-C (in particular, the ADI platform costs $50 to $60k per node).

Besides, a wide range of SDRs are available in the X/Ka bands, originally designed for rugged satellite operations (https://www.satnow.com/search/software defined radios). However, these SDRs are mostly limited to a single antenna, and some of the features are overkill (e.g., radiation shielding) for terrestrial networks.

Baseband Hardware: FPGAs like RFSoC and general processors are popular choices for baseband hardware. These baseband modules have been used in the sub-6GHz and mmWave SDRs, and they are easily reusable for upper midband SDRs.

Baseband Software Libraries: Sharing similar baseband hardware also allows for sharing software libraries like GNUradio and open-source network stacks (e.g., OpenAirInterface).

Path Towards an Upper Midband SDR

Lessons from the development of sub-6GHz and mmWave communication networks indicate that academic research should outpace commercial vendors and standardization bodies to be able to shape its future. Instead of waiting for a full-fledged integrated upper midband device to become available, it is important for the research community to adopt a phase-by-phase approach – starting with a low-profile SDR (e.g., with a single antenna array) as early as possible to bootstrap research in the upper midband; and then, progressively evolve into modularized, feature-rich SDR platforms to explore capabilities to address challenging problems in the upper midband. To support the latter goals, research activities in parallel with the initial SDR development could investigate highly frequency-agile and frequency-selective radio hardware, built-in calibration capabilities for SDR-based measurements, and improved antenna array performance.

Collaboration is crucial in this journey. SDR hardware design involves expertise in multiple domains (e.g., antenna design, RF frontends, baseband interfaces, and signal processing, to name just a few). Furthermore, we need to work closely with experts in the software/firmware design and end users to accelerate the development cycle. Ideally, the hardware research community should create a library of open hardware designs (reference building blocks, antenna arrays, etc.), allowing for mix-and-match assembly of SDRs with different complexity of functionalities. It should also be noted that developing SDRs entails different performance and features as developing customized transceivers tailored for one specific application. The former emphasizes programmability, which may come at the cost of higher SWaP-C.

Appendix I: Participants and Agenda

Picture in Lobby of Railway Building

Participants

- Abedi, Ali (Stanford University)
- Abouzeid, Alhussein (NSF)
- Baram, Michael (University of Notre Dame)
- Bharadia, Dinesh (University of California San Diego)
- Chi, Taiyun (Rice University)
- Chisum, Jon (University of Notre Dame)
- Dhananjay, Aditya (Pi-Radio)
- Dick, Chris (Nvidia)
- Doczkat, Martin (FCC)
- Doost-Mohammady, Rahman (Rice University)
- Element, Cliff (thinkRF)
- Ettus, Matt (Self)
- Fox, Scott (OUSD)
- Freeman, Steve (ARL EW)
- Ghasempour, Yasaman (Princeton University)
- Ghosh, Monisha (University of Notre Dame)
- Gilliland, Dennis (Nokia)
- Golmie, Nada (NIST)

- Gosain, Abhimanyu (Manu) (FutureG & 5G)
- Haj-Omar, Amr (National Instruments)
- Hary, Steve (AFRL/RYM)
- Hochwald, Bert (University of Notre Dame)
- Kirkwood, David (FutureG & 5G)
- Kuester, Dan (NIST)
- Laneman, Nick (University of Notre Dame)
- Luther, Erik (Self)
- Melodia, Tomasso (Northeastern University)
- Meng, Xiangbo (University of Notre Dame)
- Miller, Marcus (OUSD)
- Mueller, Bruce (Motorola Solutions)
- Nandagopal, Thyaga (NSF)
- Nuss, Ziv (Sensorz)
- Palathinkal, Joshua (University of Notre Dame)
- Pandeya, Neel (Ettus)
- Pedtke, Dan (University of Notre Dame)
- Rangan, Sundeep (New York University)
- Rondeau, Tom (OUSD)
- Sabharwal, Ashu (Rice University)
- Sammons, Tiffanie (University of Notre Dame)
- Schuman, Todd (NTIA)
- Shakkotai, Srinivas (Texas A&M University)
- Sudharman, Jayaweera (NSF)
- Swindell, James (Army DoD)
- Taylor, Wyatt (Epiq Solutions)
- Torres, Jose (MITRE)
- Van der Merwe, Kobus (University of Utah)
- Wahl, Chris (University of Notre Dame)
- Weiss, Martin (OUSD R&E FutureG)
- Wyglinski, Alex (Worcester Polytechnic Institute)
- Zhang, Xinyu (University of California San Diego)
- Zussman, Gil (Columbia University)

Agenda

Upper Midband Software Defined Radio (SDR) Workshop

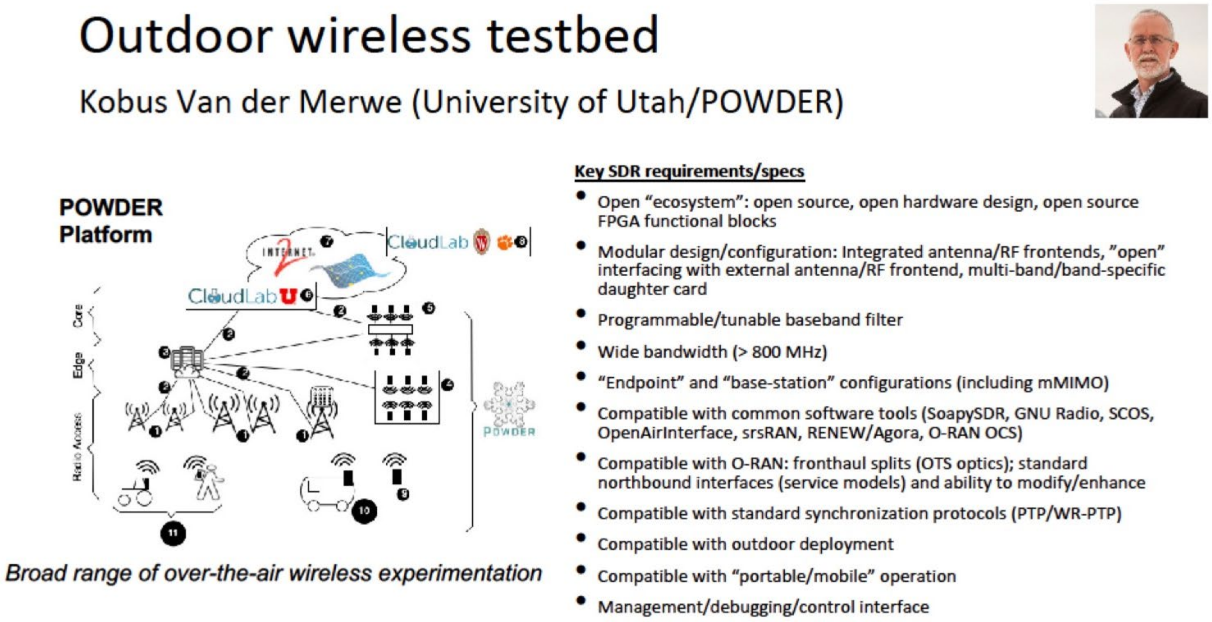
Monday, September 11, 2023

Monday, September 11 | Working Meeting and Presentations **Location:** Notre Dame Chicago Campus, Railway Exchange Building | Suite 350, 224 S. Michigan Ave, Chicago, IL 60604		
Time (ET)	**Topic**	**Lead/Presenting**
8:00 AM	Breakfast	
8:30 AM	Intro Remarks: Thank you for Coming!	Thyaga Nandagopal
9:00 AM	First Plenary: 6-24 GHz, all we need for the next ten years	Monisha Ghosh
9:30 AM	Second Plenary: DoD perspective on the Hi-Band SDR	Tom Rondeau
10:00 AM	Break	
10:10 AM	Lightning Talks: **Use Cases**	
11:15 AM	Breakout Room #1: **Use Cases**	Bert Hochwald
	Breakout Room #2: **System & Software Requirements**	Ashu Sabharwal
	Breakout Room #3: **Hardware Requirements**	Jon Chisum
12:15 PM	Lunch	
1:15 PM	**Use Cases:** Summary and Discussion	Clerk
2:00 PM	**Use Cases:** Comments & Web Form	
2:10 PM	**System & Software Requirements:** Summary & Discussion	Clerk
2:55 PM	**System & Software:** Comments & Web Form	
3:05 PM	Break	
3:15 PM	**Hardware Requirements:** Summary & Discussion	Clerk
4:00 PM	**Hardware Requirements:** Comments & Web Form	
4:10 PM	Closing Remarks and Input Guidance	Bert & Friends

Appendix II: Link to Use Cases Lightning Talks

At the beginning of the workshop there were eleven lightning talks by various participants focused on use-cases for the SDR. These talks were designed to motivate the breakout sessions that followed. Each talk comprised one slide. The link to these slides is: https://drive.google.com/file/d/1Ag5S_N3tvjLFtYPvdkKnvMgGGZroS1F/view?usp=drive_link

Welcome
to the
Upper Midband
SDR Workshop



Outdoor wireless testbed

Kobus Van der Merwe (University of Utah/POWDER)

POWDER Platform

Broad range of over-the-air wireless experimentation

Key SDR requirements/specs

- Open "ecosystem": open source, open hardware design, open source FPGA functional blocks
- Modular design/configuration: Integrated antenna/RF frontends, "open" interfacing with external antenna/RF frontend, multi-band/band-specific daughter card
- Programmable/tunable baseband filter
- Wide bandwidth (> 800 MHz)
- "Endpoint" and "base-station" configurations (including mMIMO)
- Compatible with common software tools (SoapySDR, GNU Radio, SCOS, OpenAirInterface, srsRAN, RENEW/Agora, O-RAN OCS)
- Compatible with O-RAN: fronthaul splits (OTS optics); standard northbound interfaces (service models) and ability to modify/enhance
- Compatible with standard synchronization protocols (PTP/WR-PTP)
- Compatible with outdoor deployment
- Compatible with "portable/mobile" operation
- Management/debugging/control interface

128 Low-Res Digital Chains

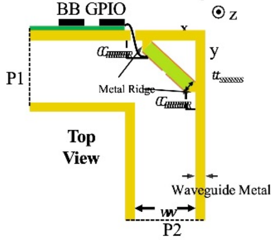
Bert Hochwald – University of Notre Dame

Use case description

- Large number of fully-digital chains to study MIMO/beamforming contour
- Low-power thru low resolution
- High symbol rate
- On/Off, BPSK each chain

Key SDR requirements/specs

- 64-128 chains
- 2 GHz sample rate per chain
- FPGA/baseband parallel processing at GHz rate



MUST BE PUBLICLY RELEASABLE

NG Communications/Sensing

[Bruce Mueller, Motorola Solutions]

SDR Platform Use Case

- Develop system concepts for short range comms, local sensing systems, LEO/UAV comms, including spectrum reuse and policy needs.
- Prototype effective component technologies, including MIMO, PA design, antenna structures, modems, processing architectures for future systems
- Investigate the cross layer optimizations to optimize system designs for varied constraints.

Key SDR requirements/specs

- Modular design to enable varied experimentation. (FMC?, PCIe?)
- 6-28 GHz multichannel transceiver w/ ~ 10 dB NF, 10-100 mW Tx power, integrated/bypassable antenna(s)
- 1+ GHz IF BW w/ direct FPGA/GPU fabric, abstract programming
- Support digital and analog Rx/Tx antenna arrays Support external PA, LNA systems.

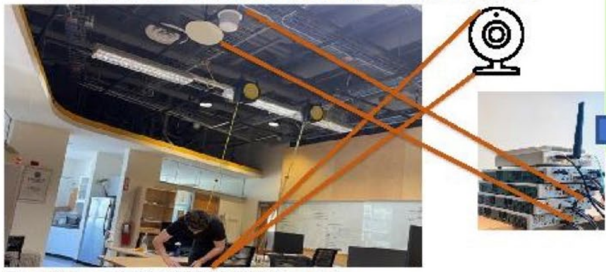
MUST BE PUBLICLY RELEASABLE

Anomaly Detection as a Service
Dinesh Bharadia, UC San Diego

What is an Anomaly for Spectrum?

Detection of a device, signal, and emission which is un-authorized or unrecognized on spectrum. The following can be built atop of it easily as an app:

- Interloper detection
- Spectrum co-existence
- Information exfiltration with spy mic and cameras

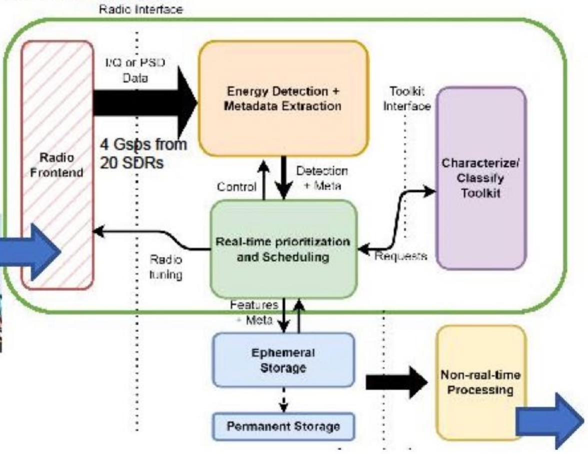


Primarily supported by IARPA SCISRS program

dineshb@ucsd.edu , +1-858-822-0168

Requirements for SDRs

SDRs should be treated as a sensor: streams IQ with massive MIMO, or building high-layer abstraction in to SDR as shown below.



Spectrum Use and Analysis above 6 GHz

Dan Pedtke – University of Notre Dame

Use case description

- Ubiquitous spectrum measurement
- Minimal configuration/easy to use
- Very low cost of use & installation
- Simple backhaul

Key SDR requirements/specs

- Low cost
- Receive-only
- Two-chain (at least)
- Mobile (battery-powered)
- Integral antenna
- 200 MHz instantaneous BW

MUST BE PUBLICLY RELEASABLE

Fast Wireless Service Scanning

Cliff Ellement, ThinkRF

Use case description

- Ability to scan, detect, and decode Wireless Services (i.e 5G)
- Scan entire Band seeking
  - Fc & Service Type detection
- Decode for Overhead Control information (Base station Cell info)
- Interference Detection
  - Protocol / RF Spectrum
- System may be automated
  - Requiring Sig Processing / AI Algo's

Key SDR requirements/specs

- RF scan rate: Thz/sec
- IBW: 100-200+Mhz
- High Fidelity for Sig Proc / AI detection
  - Low Noise floor:
  - High Dynamic range: 110dB - 120dB
- Digital Processing Power
  - Process Max samples/sec. (for a given RBW)

Use Case: Wireless Observability Platform

Ziv Nuss, Sensorz.io

Real-time, continuous solution for detection of events across the wireless spectrum

- Collecting both RF and protocol data
- Using ML for self learning and gain awareness of the wireless environment
- Generating anomalies and attacks alerts
- Pre-emptive awareness of performance degradation problems
- Automatic signals classification
- Interferers' location data

sensorz

Key SDR requirements

- Move from Software Defined Radio to **AI defined Radio**
- Integrated HW for AI (on board GPUs)
- High performance Edge processing capability (e.g. i5/i7)
- Flexible Rx channels config.
- Cost reduction for low SWaP rollout
- Integrated backhaul solution (IoT cloud architecture)
- Enable sensors mesh (e.g for geolocation)

USRP for 5G/NR & ORAN Testbeds

Neel Pandeya, Amr Haj-Omar National Instruments (NI)

- Providing an open-source reference architecture for 5G/NR testbeds based on USRP devices
- Frequency coverage across various bands in FR1, FR2, FR3, and for all channel bandwidths
- Support for both the gNB and UE, with 2x2 and 4x4 MIMO
- Support for ORAN 7.2 Split and eCPRI interfaces
- Large FPGA to off-load PHY layer processing and enable support for ORAN 7.2 Split
- Integrated front-end filtering and PAs
- Enable research and prototyping of shared spectrum, ORAN, NR-U unlicensed access, NTN
- Integrated open-source software stack and user documentation to enable rapid configuration and deployment

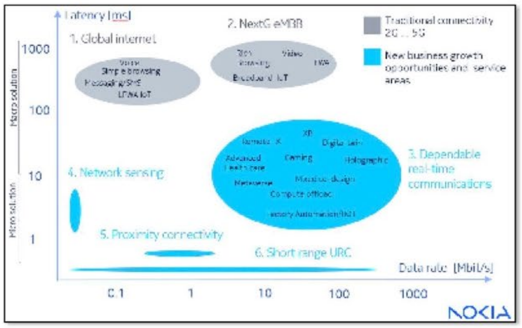
---

6G Cellular Communications – FR3 (7 – 24 GHz)

Dennis Gilliland, Nokia

Use case description

- 6G Wireless solutions to meet a wide range of use cases with different data rate and latency requirements. eMBB enhancements and extensions to support Industrial Metaverse, FWA (Fixed Wireless Access), and Network Sensing
- Efficient use of available spectrum, and ability to densify networks, to consistently enable use cases across all layers of a heterogeneous network.

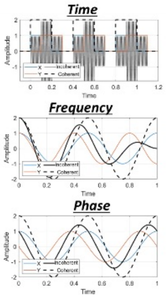


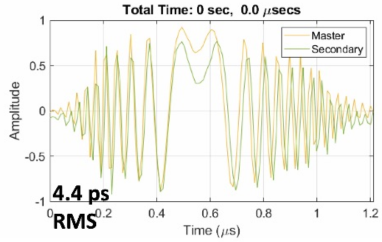
Key SDR requirements/specs

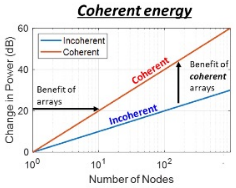
- Flexible frequency configuration with minimal impact to efficiency
- Flexible radio application for use as access or wireless backhaul (to ease cost of densification)
- Flexible support of Dynamic Spectrum Access (DSA) approaches if needed due to incumbency in the 7 – 24 GHz spectrum
- Flexible MIMO / Beamforming schemes for capacity vs. coverage solutions (i.e., 6 dB pathloss increase could require 4x number of radiators for grid alignment)
- >= 400 MHz carrier bandwidth expected
- Flexible configuration for sub-band full duplex (SBFD) and interference cancellation approaches
- Flexible Radio Access Technology capabilities to support MRSS (Multi RAT Spectrum Sharing)

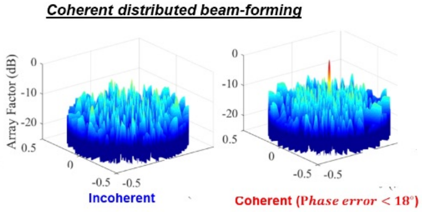
Distributed Arrays
Jonathan Chisum, Univ. of Notre Dame

Over-the-air Synchronization



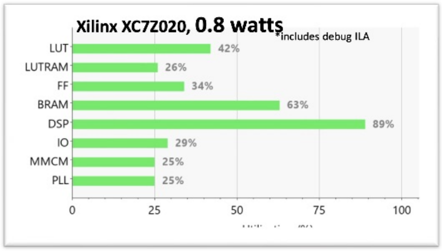






Key SDR requirements/specs

- Symmetrical radio hardware
- Deterministic signal processing and sufficient DSP blocks (FPGAs)
- IP reuse



Joint Communications and Sensing (JCAS) for Smart Streetscapes

Gil Zussman, Electrical Engineering, Columbia University

NSF ENGINEERING RESEARCH CENTER FOR SMART STREETSCAPES (CS3) COLUMBIA | FAU | UCF | RUTGERS | LEHMAN

COSMOS

Use case description

- Support for streetscape applications in dense urban environment (smart intersection, wayfinding, digital twin for transportation)
- Various sensing modalities
  - Lidar -> cost and deployment concerns (2,862 traffic signal intersections in Manhattan, 13,543 in NYC)
  - Cameras -> privacy concerns
- Situational awareness can benefit from JCAS

Key SDR requirements/specs

- Size
- Separation of Tx & Rx, Interference cancellation
- Potential for RF backhaul, flexibility to support of other use cases
  - Lightpole mounted is difficult to revisit

Lightpole mounted

PUBLICLY RELEASABLE