Question 1:

One of the biggest challenges is that free and open-source standards-compliant implementations simply do not exist. The consequence of this is that researchers (such as those in academia, small companies, and governmental laboratories) do not have the tools to build demonstrations of open standards-based RANs. For example, most academic researchers do only theoretical and/or simulation work; experimentation is very rare. As a result, the engineers that graduate, even from top universities, do not have the experience and skills needed to build and operate such systems. Only a small number of people, at the large companies, have the skills needed for this.

The solution to the problem is two-fold. First, there needs to be a *free* and open-source standards-compliant cellular implementation. This is the only way that Universities can produce engineers who are skilled in this area. Second, there needs to be greater access to *affordable* and *advanced* software-defined radios (SDRs) that are used to run such open and standards-based RANs.

Currently, SDRs are very expensive, especially those that feature advanced RF transceivers like mmWave beamformers and MIMO front-ends. We need to make such SDRs affordable, and support those who strive to do so. Second, SDRs that are available are many years behind the demands of the research community. For example, the new-mid bands for 6G are being considered in the 6-24 GHz bands. As far as we know, there are no commercially available SDRs that operate in these bands. It is unclear to us as to what the commercial status and availability of Hedgehog SDR is. As a result, the research community does not have access to the hardware needed to build demonstrators in this space. All the work ends up getting cannibalized by the giant companies that have the budgets to build their own SDRs in-house. Academics, smaller companies, and governmental laboratories fall behind. This needs to change.

In summary: the NTIA should consider funding the creation of *demonstrations*, where affordable and commercially available SDRs are used, in concert with free and open-source software implementations. This is the only way that workforce development that is needed in this space, can be done.

Question 2

A key challenge in the wireless R&D ecosystem is that experimentation is rare. This is because: a) SDRs are too expensive or are technologically behind the curve; b) reference standards-compliant software implementations are not accessible to the community at large; c) the lab -> fab -> system pipeline is broken.

SDRs, which are the critical tool needed for wireless experimentation, are hard to build; this is specially true when we consider highly advanced transceivers like mmWave beamformers, full-rank MIMO front-ends, and so on. But the reality is that SDRs *should not* be this expensive to build.

Just as an example, let us consider SDRs with mmWave beamforming front-ends. It was in the late 1990s that mmWave phased array chips were first developed and tested. However, it was only around 2015 that SDRs with mmWave phased arrays became available to the systems community. SiBeam was the company that built these front-ends, spending what is rumored to be >100M on its development. This is emblematic of a larger trend: a) there is a 15 year technology-translation gap from the time that RF chips are developed to the time that such technologies get incorporated into experimental systems; and b) companies spend inordinate sums of money to re-design silicon, even though such chips have been demonstrated many years earlier by academics. This situation is insane, and needs to change.

What is the solution? We believe that SDR companies should work directly with top RFIC academic groups to "translate these academia-designed RFICs into real-world systems". Taxpayers have already paid for highly advanced RFIC design efforts. Universities (UCSB, UCSD, UC Berkeley, Columbia, etc) are the world leaders in RFIC design. Tremendous amounts of intellectual capital (and taxpayer funds) have already been spent on such development. We need to harvest the fruit of these investments to translate these RFICs into real-world systems.

One example of this model is a DARPA award to UCSB and Pi-Radio. At UCSB, Prof. Mark Rodwell's group has developed excellent 140 GHz TX chips, RX chips, power amplifiers, and multi-channel modules. A tremendous amount of effort has gone into these very impressive efforts. Pi-Radio worked with UCSB to create a one-off SDR prototype demonstration using the UCSB 140 GHz modules. Buoyed by the success of this demonstration, DARPA awarded Pi-Radio and UCSB an SBIR to commercialize 140 GHz SDRs and bring them to the systems community. This is an example of a DARPA-funded initiative to "translate academia-designed RFICs into real-world software-defined radios".

Such efforts are meaningful because companies do not have to spend 10s of millions of dollars to redesign RFICs that already exist. Such technologies are not held hostage to the 15-year technology translation gap. Systems can be built at one-tenth the cost, and in one-tenth the time.

We would strongly encourage the NTIA to fund similar initiatives. This is a proven successful model. It is only through the existence of such SDRs that advanced wireless testbeds can be built affordably and quickly. Workforce development relies on such testbeds being available. If such efforts are not funded, then experimentation will be limited to internal labs at Qualcomm/Ericsson/Nokia, etc., that can afford to build out their own SDRs and testbeds. The larger community will get shut out, yet again.

Question 3

The NTIA is absolutely right to ask this very poignant question. The sad reality is that US universities are simply not producing enough engineers who know how to build real-world wireless systems. The main reasons are: a) commercially available SDRs are too expensive and/or feature outdated RF transceiver technologies; b) free and open-source reference software implementations, especially those that are standards-compliant, are non-existent. This leads to much of the wireless work (being done at universities) to be overly reliant on theory/simulations. Students almost never build SDR-based demonstrations, and therefore do not have real-world skills that are valued in the industry.

To alleviate these challenges, the NTIA could consider funding "real" testbed initiatives, where the funding for SDR development is also present (as opposed to relying on in-kind donations from the industry). The NTIA could specify the SDR technical specifications if needed, and let companies bid on who can build it better and most affordably. There is a lot of effort needed to make the standards-compliant implementations work. This needs to be funded as well. The mere existence of something like open air interface does not mean that deploying it is cheap or easy. The folks who run the testbeds need funds to develop this software, perform porting across hardware platforms, inter-operate it with different front-ends, etc. Such efforts need real funding, so that staff engineers can be hired with competitive industry salaries. We cannot have a system where the job of deploying and maintaining testbeds falls upon professor / PhD student labor. This is untenable. The NTIA could speak with people who have real experience running real testbeds, and therefore understand what it really takes. And the NTIA would also do well to understand the limitations of existing funding mechanisms (such as through the NSF PAWR initiatives), so that we get better and better with every iteration. I recommend the NTIA speak with Ivan Seskar at WINLAB / Rutgers University, who in my humble opinion, is the gold standard in building, deploying, and running wireless testbeds. There is nobody more knowledgeable and experienced.

Question 4

As I mentioned in my response to Question 2, a key aspect is to fund industry-academia collaborations for technology translation. Academia-designed chips can be used to build SDRs (and other hardware) that can be deployed in a testbed. I would strongly encourage the NTIA to fund such collaborations.

However, a word of caution: intellectual property can be a challenge. The key is to fund collaborations where the IP issues are already worked out, or can be worked out easily. In my experience, making work products free and open-source (to the legal extent possible) is a great model. This will encourage collaborations that focus on engineering. And it will keep out the IP-driven mentality that leads to slower technology development and higher costs for everyone. This is especially true when we're talking about testbeds needed for research and development.

On a philosophical note, I think it's perverse for the US government to fund an effort that will ultimately lead to higher prices for US-based consumers. This is why we strongly believe in IP-free implementations, and open-source to the extent possible. Pi-Radio, for example, makes all software and hardware design schematics free and open-source, to the extent permitted by the funding agencies.

Question 5

Pi-Radio is in the business of designing and manufacturing software-defined radios. The supply chain crisis hits us *very* hard. We have had to come up with 10 (yes, ten) design iterations for our latest SDR product because parts keep going out of stock. Wait times for parts are long (often times, one year). This necessitates us redesigning the SDR multiple times to use parts that are available today. Each time we want to manufacture greater quantities, there are part shortages that lead us to re-design. This is driving up the cost and time needed to manufacture SDRs (the key testbed equipment). Further, inflation is very high. So, perhaps one way to work around this is instead of having fixed-price contracts to make equipment for testbeds, structure the contracts as "time + materials". This way, companies will not submit inflated quotes to hedge against future inflation and redesign cycles; and companies will be sure that if such redesigns are needed, they are paid for. We do not want companies (like Pi-Radio) to be scared away because of firm-fixed-price contracts. We have learned this lesson the hard way.

Question 6

I am personally not an expert on standards-compliant cellular implementations. But what I do know is that they are rare, buggy, and hard to use. Even to download open air interface, compile it, and run it on the recommended hardware is an effort that can take a lot of time. There is very little support, and very little documentation. Gettings things to work is time consuming and hard. So please make sure that these efforts are funded keeping in mind that these things take non-trivial time and effort.

Question 7

I can address this issue from the hardware side of things. We need affordable SDRs that can run such standards-compliant software implementations. One potential way is to standardize the baseband processing hardware that is used (for example, rely on RFSoC-based FPGAs). This way, any RFSoC-based

SDR can be used to build the SDR baseband component. Yes, some work will be needed to port from one platform to another, but in the minimum, the high-level architecture will be based on the RFSoC. This way, we can have interoperability and porting. Otherwise, to port a software implementation from one platform (for example, the NI PXIe platform) to another (say, the RFSoC-based SDRs) will be an effort that basically involves a full ground-up reimplementation.

So: to maintain stable, cost-effective, and interoperable RAN products, have a standard hardware architecture at least for the physical layer (say, the RFSoC).

Question 8

On the software side, Open-RAN defines the interfaces between the various components. This is great. However, what's really critical are the actual implementations, as opposed to just the interfaces. We need free and open-source implementations, not encumbered by IP headaches. I'm not an expert in this area, but it is my understanding that most companies are not willing to make their L1 and L2 implementations free and open-source. Someone needs to be funded to do this. But since this is not my core area of expertise, I will not say any more on this matter.

Question 14

Testbeds that involve hardware that addresses the needs of the future. Too many testbeds today feature technologies that were relevant for 3G/4G. We need testbeds that will address the spectral needs of the future (6-24 GHz for access, >100 GHz for backhaul), as an example. For more mature technologies, commercial products already exist, so it really won't move the needle much.

Question 15

Provide funding to existing testbeds (for example, the NSF PAWR-COSMOS testbed) to add functionality related to 6-24 GHz SDRs, +100GHz SDRs, and so on. And very importantly, provide the funds needed to procure not only the SDRs, but critically to perform the software tasks. Running open air interface (OAI) on SDRs requires a lot of effort. Running an interoperability demonstration requires months of effort by experienced engineers. These efforts should be funded. Most testbeds rely on PhD student labor – this is untenable. The NTIA needs to fund high quality staff engineers who will make industry-grade money. Perhaps the NTIA can also make reasonable rules about what overhead rates proposers are allowed to ask for, to make sure that costs are kept at reasonable levels.

Question 22

Small businesses and startups need to be encouraged. As the NTIA rightly notes, the current cellular ecosystem is highly consolidated with a small number of giants. These monopolies need to be challenged. Open-RAN is a step in the right direction. But still, small companies need funds to succeed. In our experience, raising VC funds is very challenging. Smaller telecommunications vendors will not have the sort of hockey-stick growth that VCs want to see. So, these companies need to be funded (through real contracts, as opposed to grants) in order to survive and compete. The NTIA can fill this hole that VCs fail to fill (VCs are concerned about profits and profits alone. There is a national interest in funding smaller design/manufacturing companies in the wireless ecosystem).

Question 23

Perhaps the NTIA could fund "projects", instead of "teams". A project has a concrete deliverable in terms of hardware being demonstrated, and the associated software being made open-source. This way, the participants are incentivized to do so. We need to move from “open interfaces” to “open interfaces and implementations”. This is true not only for software, but also for hardware. For example, hardware vendors can be required to make their hardware schematics open. This will encourage sharing and transparency. And prevent money being spent on useless re-engineering and re-implementation efforts. To conclude, the NTIA should fund “concrete projects” as opposed to “teams/consortia”.

I’ll make a loose hand-wavy observation here. Gigantic teams/consortia lead to more talking and more overhead. It leads to more meetings and more wasted time. What actually gets built, demonstrated, and delivered, is smaller. Instead, the NTIA should fund concrete projects with very clear deliverables, much like the projects funded by the National Spectrum Consortium. Encourage projects that promise open-source outcomes (hardware and software). Finally, support small businesses and startups more. The large companies have enough money! We need an ecosystem with more competition and more choice.

Question 24

Do not require matching. In fact, preclude such sharing. This will only lead to the moneyed organizations getting more money. Smaller players will get shut out again. The NSF does this for most awards, and for good reason.

Question 25

Yes, require that the majority of the work takes place in the US. Let’s also remember that a lot of the wireless technologies are export controlled. We don’t want to have a situation where small companies from around the world spend their time and money trying to navigate our legal system. Let’s focus on what we should be doing best: build real-world systems quickly and affordably.

American made is a very worthy cause that we support wholeheartedly. This will support US-based manufacturing, and reduce reliance on foreign players. However, we should go into this with our eyes open. For example, Pi-Radio makes SDRs. We design it in the US, and get all the manufacturing done in the US. However, some parts used in our SDRs (resistors, capacitors, LDOs, for example) are manufactured overseas. So I think it would be harmful to say that *all* components should be US made, because this is just not possible. But the NTIA could require that all design and manufacturing take place in the US. And components should be US made for hyper-specialized parts. But for generic components (capacitors, inductors, etc), there is no option but to buy foreign-made parts.

Question 27

As mentioned earlier, spectrum dominance is something that we need to very carefully explore. It is no secret that 5G mmWave has largely been a commercial failure. This is because the signal propagation is so bad that we need a very dense deployment of mmWave base stations; this is very expensive to do. The community is now seriously looking at the new mid-band (6-24 GHz bands) as a serious candidate for 6G. The main challenge here is that there are a lot of incumbents (satellites, RADAR, and other governmental use-cases) in these bands. If we are to operate cellular networks in these bands, we need to do spectrum sensing, sharing, and coexistence. These are hard problems that will require a lot of experimental R&D. I would like the NTIA to encourage efforts that look into maintaining spectrum dominance. By funding testbed efforts that focus on these emerging frequency bands. Another potential frequency band is the D-band for backhaul and line-of-sight MIMO. This can provide huge backhaul capacities, without the headache of having to lay down fiber. This can also lower the cost of deployment of future generation networks, since backhaul is a major cost driver. Therefore, please have a focus on "spectrum".

I would like to conclude by thanking the NTIA for all its efforts. Thank you for soliciting feedback from the community in terms of what is the wisest way to invest taxpayer dollars.