NGI THINK NEXUS

White Paper

Advanced Wireless Networking

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Think NEXUS, an EC-funded project, aims at reinforcing EU-US collaboration on NGI-related topics in three focus areas: Science and Technology, Innovation and Entrepreneurship and Policy. The aim is to boost strategic research, industrial partnerships and policy compliances in order to gain socio-economic benefits in both the EU and US regions.
In the framework of this project, we are regularly publishing several short articles aiming at comparing the US and the EU approaches in different topics of NGI. The present document is focusing on Artificial Intelligence.

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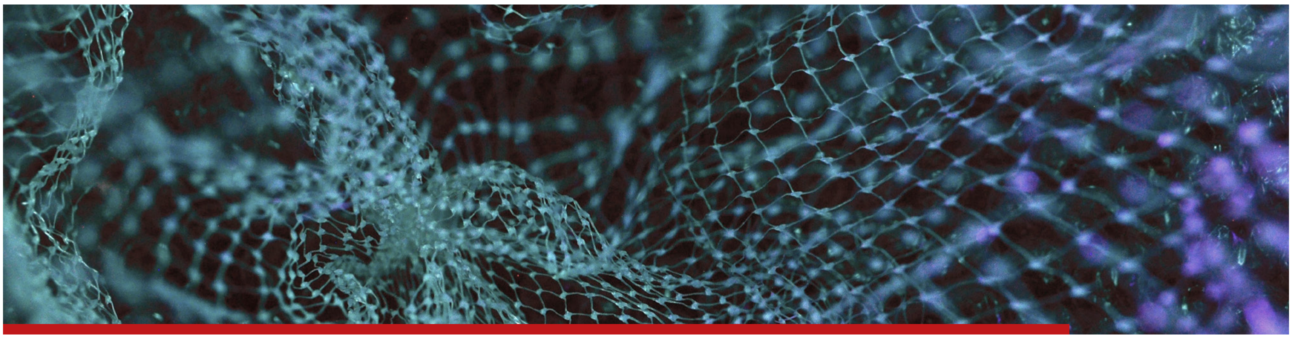


Advanced Wireless Networking

Rapid advances in advanced wireless networking herald a renaissance in extending the power of the Internet to completely new classes of mobile and real-time applications. It is already beginning to unfold with the arrival of 3GPP releases 15 and 16 commonly known as 5G. But the technology still on the horizon promises considerably more. The implications will have substantial economic, political, and national security impacts.

Economically, the exploitation of new wireless technologies will enable, as 5G has promised, the ability to enable widespread ultra-low-latency and machine-to-machine communication. The machines themselves are increasingly becoming first-class objects communicating with each other as well as with humans, augmenting as well as extending capabilities such as vision, reasoning, and collaboration. The ultra-low-latency is faster than human thought. On the darker side, ultra-low-latency and machine-to-machine communication will also create fearsome new weapons that can see, reason, and collaborate with each other. Just as the discovery of "fire" was transformational to the Neanderthals, these developments are both a blessing and a potential curse from which we cannot retreat. This means that advanced wireless technologies have both national defense and national economic value.

Politically, advanced wireless networking threatens the business standing of the very large incumbent providers. New technologies can and will change the playing field and require massive new investments. Some believe these massive new investments can and will be made by the incumbents if properly incented by regulation and this approach is politically and economically palatable to the large incumbents. Those same players are often well insulated from competition by both the natural monopolies of building out physical infrastructure (just as building out roads is unquestionably a government monopoly) and by regulatory hurdles put in place to discourage new competitors.

However, a shift in how wireless is being used is eroding those monopolies. In the United States, competition to provide high-speed Internet to homes and businesses is rare. For example, at the author's home, the monopoly wired telephone company offers 1.5Mbps service as their highest data rate. Fixed wireless providers will provide 25Mbps or 50Mbps, but only one company, the cable company, provides 1 Gbps service, and that's only in the down direction. As we'll see, there's currently little economic incentive for this to change.

National Security requires resilient communications for everyone, privacy for national security communications, and the ability of the government to be the only party who can snoop on everyone else provided they do so quietly. In the United States, domestic spying has been somewhat limited by various laws, but after the September 11, 2001 terrorist events, laws and regulations have been considerably loosened and the exact limit of permissible spying is part of the political debate.

On the other hand, U.S. interception of foreign wireless has no such restrictions, and arrangements such as the "Five Eyes" intelligence alliance would seem to allow nearly anything world-wide to be intercepted by a friendly foreign government and then shared domestically; this arrangement seems to be tolerated as long as only national security information is being collected. However, the United States (as well as others) fear potential enemies such as China through companies such as Huawei may be able to gain an intelligence advantage and use it for clandestie cyberwarfare such as affecting elections.

Organization

The remainder of this paper explores future advanced wireless under the following themes:

1. The last 25 meters is wireless
2. New communication pairs

And then some fairly technical sections:

3. Advanced wireless frequency considerations
4. Advanced wireless timing considerations
5. Advanced wireless spatial considerations
6. Open access coordination and collaboration
7. Multi-modal considerations

The Last 25 meters is Wireless

Mobility within homes and businesses turns out to be just as important as mobility in vehicles, airplanes, and transit. The advantages are several:

a. Nothing has to be pre-wired in the structure. What you would have put into the walls a decade ago is nothing like what you might put in the walls today. And rather than let that become obsolete, let's just go wireless.
b. There are no wires or cables needed that might trip people or pets.
c. You can't plug the wrong thing into the wrong socket. There are no plugs or sockets.
d. Your home or business won't stop working if you re-arrange things. There are no patch panels in the closet to be rewired if you want to re-use space differently.
e. You can take it with you if you move or are displaced. Emergencies and disaster do happen.
f. High frequency wireless can provide very accurate geolocation and wayfinding.

There are also a few disadvantages: there are lots of batteries to recharge or replace; your wireless things can interfere with or be interfered by your neighbor's wireless things; it's much easier for the government to spy on you; and changing your wireless encryption key involves a lot of setup on each device.

Nevertheless, the world is moving in the direction that the last 25 meters is wireless. The author's watch talks to Bluetooth and WiFi and it uses my cell phone to synchronize the date and time as well as notify me of text messages and the like. Many Roku devices no longer come with the ability to connect Ethernet. The wired attachment dongle for an Amazon Fire stick raises the price by about half. Wired headsets can no longer be plugged into the latest versions of cell phones; you must go wireless.

New Communication Pairs

The predominant wireless communications options visible to consumers have been cellular, WiFi, and Bluetooth. Cellular talks to your phone, tablet, and possibly Chromebook. Bluetooth talks to your headset and watch. WiFi talks to everything else, including the Internet when you're inside an airplane.

For businesses, commercial and industry-based WiFi solutions have predominated.
The future will see some new wireless pairs.

a. Vehicles to vehicles, pavement, and curbs. For connected vehicle applications, extremely reliable wireless is in order. It must be resilient to cyber-terrorists who may try to jam communications. Everyone is familiar with today's cellular dropouts and blind spots. While much better than a decade ago, connected vehicles can't afford drop-outs. Therefore we'll likely see connected vehicles talking to one another in rural settings, and communicating with community-based connected traffic management systems via the most reliable ways possible.
   This author thinks the logical answer is smart pavement. By using very high frequencies, the vehicle itself provides an RF shield against an adversary trying to jam communications in the few centimeters between the bottom center of the vehicle and the pavement over which It's traveling. As roads are re-paved every decade or two, smart roadway antennas can be implanted. The very high frequencies used (perhaps even optical frequencies) can be re-used under each vehicle and can carry an immense amount of data. (Data carrying capacity of wireless communications is proportional to the frequency used.) If pavement turns out to be impractical, smart curbs may substitute but be more open to adversarial jamming.

b. Anything to satellites. No fewer than 5 constellations of low-earth-orbit (LEO) satellite constellations are being deployed commercially to provide secure, low-latency Internet from the sky. While there was always a business case in rural areas (and for which Intelsat is already available at very low speeds), incumbent carrier economics allows satellite to play a significant role even in urban areas. The days of not responding to texts by being able to claim, "I didn't have any service on my hike" may be numbered.

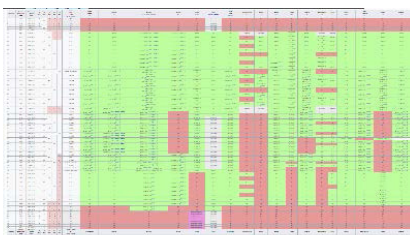
c. Anything to Balloons. During the COVID-19 pandemic, the Alphabet subsidiary Loon launched connectivity balloons in Kenya. It worked well, and balloons may be one of the best connectivity pairs along with satellite to be able to keep things going if earthquakes or hurricanes destroy land-based infrastructure.

d. Mesh networking buddies. The COVID-19 pandemic has encouraged a resurgence of mesh networking in underserved areas. These include both urban areas where personal economics and priorities had not budgeted limited resources for Internet service and in those more rural areas just beyond the reach of commercial services.

e. Anybody and anything (including robots) to their built environment. While WiFi serves today's needs, almost everyone agrees it doesn't have enough capacity to accommodate growth for tomorrow. Higher data rates and more usage demands more bandwidth which in turn suggests higher frequencies which come with the disadvantage of not easily penetrating into (or out of) the built environment. In the future, not only will homes have provisions for electricity, running water, and sewer, but they'll have provision for gigahertz and maybe terahertz indoor communication. There may be extremely small cells with line-of-sight to most all objects in the room and provide them with remoted intelligence (if not wireless power). A major user of this capability may be smart assistants in the home in the form of robots and other exceptionally smart devices. As everything becomes "smart" including light switches and RFID replaces UPC codes for anything costing more than USD $1, you'll need an intelligent infrastructure to support them.

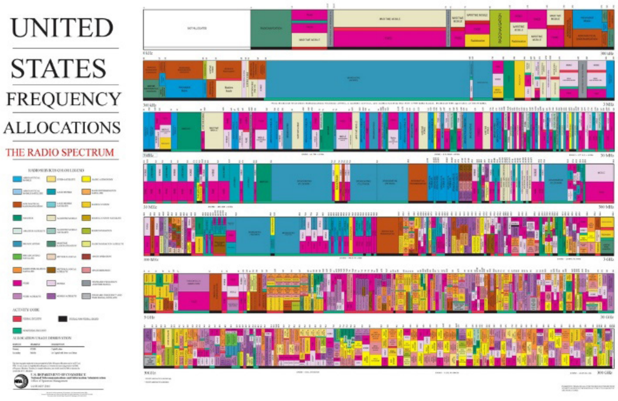
Advanced Wireless Frequency Considerations

Most United States Spectrum is statically allocated to specific uses and highly regulated. These static allocations are kept in harmony with the International Telecommunications Union Frequency Allocation Table to allow consumer and other wireless equipment to be made and sold in multiple countries and be used interchangeably around the world. However, the use of spectrum is sovereign to each country and differences abound.



This figure from the English Wikipedia article on "List of WLAN Channels" shows just how complex the 5 GHz WiFi band permissions have become around the world. From left to right are groups of countries and from top to bottom are potential 5 GHz Wifi channels. The figure is deliberately too small for you to read any of the actual information; the point is to observe the patchworks of colors showing permissible spectrum and to imagine the difficulties this causes for cross-border wireless equipment commerce let alone the problems for wireless transmissions creeping across arbitrary national borders. The figure shows the WiFi band and this band might be expected to have the greatest backing for commonality among countries. Other spectrum bands are similar and sometimes worse.

But it's not just international assignments that lack reasonable structure. United States Frequency Allocations are shown in the attached figure from the United States Department of Commerce. Spectrum allocations are fought over based on politics, economics, and national defense. Within a band, particular allocations to specific companies are often auctioned in a process which is funding the United States FirstNet first responders network.



Some spectrum is likely to be managed by open access spectrum managers which allow competing wireless carriers or competing applications to share access to spectrum on a dynamic basis. For situations where there are not enough allocations available to suit all parties, spectrum can be allocated on a number of different policies such as fair access or price auctions or maintenance of certain qualities of service.

Leveraging higher-frequency millimeter-wave small cell communications for fiber-like data rates.

Wireless communications has both a blessing and a curse compared to fiber-based digital communications. The blessing is often based on mobility and convenience; one isn't tethered to something physical that has to move with you. The curse is the comparatively limited distance over which high data-rate wireless is feasible. The higher the data rate, the higher the radio frequency required to encode the data rate. And the higher the radio frequency, the less penetrating power it has. Low-band spectrum will go hundreds to thousands of miles in the air and work around and through obstacles. High-band spectrum can encode very high data rates, but can be stopped by forest canopy or even a single large shade tree. Even higher-frequency spectrum is also known as visible light, and the ability of many lightweight objects to completely block it makes is valuable only for conditions when the people and devices communicating can see one another.

So far, low-band and mid-band wireless has been valuable enough to demand very high values at auction and has triggered many political disputes. However, given its limited data rates and scarcity, it is becoming increasingly important to overlay traditional cellular and other radio networks with millimeter-wave (27 GHz and above) small cells. Small cells derive their name from the fact that they can only cover a limited or small area. They can be fed by fiber or connected to each other in a mesh network to provide fiber-like speeds over small areas where there are few impediments to their propagation.

At higher frequencies like 60 GHz and 100+ GHz, it becomes clear that there will be separate indoor and outdoor small cell networks.
Inside, architects will begin designing-in locations for small cells that can "see" specific indoor regions and avoid dead spots. The inability of indoor small cell communications to get outside (and vice versa) will mean that we can re-use spectrum efficiently throughout the building and even in the building's immediate vicinity.

It may become economical to merge lighting with ultra-high data rate communications. The ambient indoor lighting might literally become an exceptionally high rate data network capable of handling multiple gigabit to terabit per second streams simultaneously.

Outside, one might envision small cells both above and below canopy levels to maximize line-of-sight communication possibilities. Multiple small cells might make simultaneous connections to mobile devices (including automobiles and other vehicles) to provide continuous communications. It would seem logical to embed longitudinal small cell antennas within "smart pavement" and "smart sidewalks" to communicate with the vehicles and people above. Perhaps shoes will not only generate power as they absorb footsteps but will also provide uninterruptible communication through sidewalks. Before we re-pave all the streets and sidewalks, small cells attached to city buildings and erected on rural vista points may provide the "line-of-sight" communications needed to take advantage of the data rates possible at very high frequencies.

It's clear that there will be both wired (fiber) backhaul and wireless (often mesh) backhaul to feed these small cells. Somewhat paradoxically, small cells are perhaps the best argument for ubiquitous fiber. Fortunately, we don't have any upper bounds on fiber transmission rates staring us in the face for the foreseeable future.

Advanced Wireless Timing Considerations

Traditionally, wireless spectrum has been allocated through government grants or by auctions representing the right to use a given frequency in a given location. That's a great solution if the frequency will be used all or nearly all the time such as a broadcast TV or radio station.

But many uses are sporadic and more similar to WiFi where a large number of devices may make use of the spectrum for small periods of time each. Each device checks to see if anyone else is transmitting right now, and if not, starts its own transmission. Of course, there's still a chance that two devices will start transmitting at the same time and a collision will occur. During the collision, the spectrum is wasted. While waiting to make sure no one else is going to transmit, the spectrum is wasted.

LTE (Long Term Evolution) protocols and 5G avoids collisions by dividing time into slots which can be allocated by control nodes to other devices. Spectrum utilization under LTE and similar improvements in WiFi 6 can be much higher. Unfortunately, the backwards compatibility requirements for WiFi means that older devices are not capable of honoring these slot allocations. Also, a central authority must be responsible for allocating the time slots making use of the spectrum by mutually distrustful organizations difficult.

Advanced Wireless Spatial Considerations

As we just saw, the data rates available in wireless communication depend upon the frequency being used and coordinating time slots. However, there are valuable exceptions which allow the data rate to be multiplied by factors today of about 5 and in the future of perhaps 100 or more.
The first technique in the tool bag is an old one: to use directional or sector antennas to send different data over the same frequency is different directions.

Providing your recipients are arrayed in multiple directions from a wireless cell, one can use the same frequency in different sectors to reach different recipients and to have different recipients be able to send separate signals to the cell. This technique can multiply the use of frequencies within the area serviced by a single cell by single-digits using today's technology.

The military and a few other players are also using phased antenna arrays to advantage. The greater the number of elements in the array, the more narrow the size of the beam and more beams that can be used on the same frequency. This technique is used to advantage in radar systems. The electronics needed to feed multiple data streams simultaneously through the same phased array in different directions. As a side advantage, the communications is more power-efficient because data is not being sent in all directions. However, as a disadvantage, mobile devices must be carefully tracked or have accurately predicted locations to guarantee beams will be sent to their current location.

A variation on this technique sends different data on the same frequency over different physical paths simultaneously due to reflections from buildings and other reflective surfaces. This variation is known as MIMO (Multiple Input, Multiple-Output) and is already used for small numbers (such as 2x2 and 3x3) for WiFi communications in the newer WiFi standards. WiFi access points sprouting multiple antennas might be using them for MIMO communications. (Or, just to make you think it is.) Each physical path, even if it varies by only a few inches, has its own characteristics of time delays and echoes which can be exploited to multiply the capacity of the frequency being used by a small integer.

In the work currently being conducted in massive MIMO by organizations such as Rice University (partners in the US Platforms for Advanced Wireless Research (PAWR) project with the University of Utah), up to 100x100 massive MIMO will be tested. Limitations on the multiplication factor are still areas of research.

In the future, it may be possible to construct massive MIMO phased array antennas to leverage both of these similar techniques.

Open Access Coordination and Collaboration

Some communication paths will be natural monopolies. A smart build environment seems like one of them; you won't be asking multiple carriers to provide separate antennas and base stations in your home or business. Vehicle to pavement probably doesn't mean separate antennas for each competing company. How many balloons will be economical? We already know that five companies plan to spend tens of billions of dollars each on separate low-earth-orbit satellites. (With each company planning for thousands of satellites, some astronomers are worried that the sheer number of satellites reflecting sunlight will interfere with their observations.)

We're in this situation in the United States because incumbent telephone and Internet providers (today mainly the cable companies) are vertically integrated and run everything from paying for the rights to programming to burying their media in your front yard.
No one else can afford to do that. Okay, maybe Google Fiber. But, even Google Fiber learned that when you split the market, the fixed costs really predominate.

A similar situation exists in wireless in the United States. Companies bid for spectrum at auction with the winners able to finance very high prices (which shut out competition) based on their financial ability to tie up frequencies which they may want in the future. Although the Federal Communications Commission's attempt to give discounts to nonprofit bidders is laudable, the financing needed by those nonprofits bidders sooner or later often comes indirectly from larger bidders.

A smarter solution is open access. One organization, often a municipality, puts in one set of infrastructure and then multiple services compete for subscriptions from homes and businesses. More than a hundred municipalities have now installed city-owned networks providing the fourth utility to homes and businesses. A growing number of these are now open access which is a hybrid mode preserving the ability of private enterprise to thrive and innovate over an infrastructure whose cost is amortized by all competitors. In addition, access equity is increased and may even be the dominant reason for municipal services.

In wireless, the situation is about to be coming more pressing in the same direction. Higher frequencies carry higher data rates. Gigabit 5G uses the 25-39GHz band to support multi-gigabit wireless access. This band requires small cells due to limited penetrating capabilities. Small cells require more rights of way and permissions to deploy. The incumbents in the United States are avoiding this form of 5G because of the significantly greater investment small cell requires. As the range of the wireless signal halves (due to higher frequency), four times as many small cells are needed to cover the same area. 5G is often referred to as a "fiber support technology" since each small cell needs to be fed with fiber or via a more limited wireless backhaul.

Successful, competitive small cell is going to require open access wireless networks. The main alternative will be municipal small cell, or, small cell provided only by a monopoly provider in any given area similar to the way the United States is currently divided by the dominant cable provider today.

Even at lower frequencies, it makes considerable sense to use an open access policy. The United States is about to experiment with limited priority licensing and general access to the set of Citizens Bank Radio Service (CBRS) frequencies now in disuse between 3.5-3.7 GHz. Out of ten sub-bands available, the government will auction priority access licenses to six. All ten can be used via a dynamic license coordination mechanism. These GAA users pay nothing for the spectrum but are not guaranteed a clear frequency for use. If the GAA uses are still effective, this may be a roadmap for future frequency allocations.

Let's go one step further. Can we have the spectrum efficiency of LTE, 5G, and WiFi 6 for multiple uncoordinated uses like GAA in CBRS? The possible solution is an open access coordinator to permit effective collaboration. It's an open question who would run an open access time slot coordinator, but the benefits in terms of spectrum efficiency are undeniable.

Open RAN

Going one step further, the radio access network (RAN) supporting various advanced wireless applications might be itself be an open access resource subject to time, spectrum, and space sharing managed by a combination of business and fairness principles. In this model, the radio access network protocols and characteristics are pre-defined (e.g., 3GPP release 16) and a variety of competitive service providers utilize an open access RAN. This approach is particularly important for advanced wireless growth even when there is limited real estate and/or limited fiber access for deploying the radio access portion of the network. Widespread adoption of standards like 5G will make these kinds of arrangements possible.

Open RAN is especially important for small cell deployments. Those capital requirements for deploying small cells is formidable, and would be even more formidable if each carrier had to deploy their own small cell network. By using Open RAN, carriers can compete for customers while enjoying the efficiency of deploying only one physical small cell network.

O-RAN is currently a hot topic. US Ignite has joined dozens of other telecom companies including Deutsche Telekom, Orange, ATT, and China Mobile to form the O-RAN Alliance.

Having interoperable standards will be a big boost for open access systems and allow multi-vendor environments which may help lead to multi-operator environments. It would help solve the 5G investment problem while maintaining competition in both the equipment chain and, if regulations allow, in choice of networking company providing the service.

Multi-Modal Considerations

The wireless world is one of inherent tradeoffs. You can have high frequency and high data rates but you lose the distance it can travel and its penetrating power. You can encourage new investment by offering monopoly or near-monopoly opportunities but lose the power of competition. A municipality financing its own municipal network to the home may plan on repaying its bonds over 25 years but find itself stuck in that technology when it needs to be upgraded after only 15 years. Over-investing in today's technology may limit the ability to invent in tomorrow's technology.

Given these inherent tradeoffs, one might consider importing an important guide from the financial world: Modern Portfolio Theory. Quoting from the English version of Wikipedia: "Modern portfolio theory (MPT), or mean-variance analysis, is a mathematical framework for assembling a portfolio of assets such that the expected return is maximized for a given level of risk.
It is a formalization and extension of diversification in investing, the idea that owning different kinds of financial assets is less risky than owning only one type. Its key insight is that an asset's risk and return should not be assessed by itself, but by how it contributes to a portfolio's overall risk and return."

In the telecommunication world, this implies that diversifying telecommunications investments are likely to have a higher long-term payoff. Rather than going all-in on fiber, use fiber plus wireless. Rather than doing all small cell, do a mixture of small cell and existing large cell. Rather than repaving all streets at once for connected autonomous vehicles, just do the roads with the greatest traffic demand.

Over time, wireless has continued to improve. Tomorrow's version, as imagined in this paper, is likely to be much better than today's, but Modern Portfolio theory says there is no reason to wait. This is especially true in rural areas of the United States where the cost per connection for fixed infrastructure is so high. We expect that better coordinated use of lower frequencies will make a bigger difference than better use of CBRS or other higher frequencies. Satellite communications will be important for small bursts of important information like text messages and real-time video that can't reach a fiber resource.

Bulk data that doesn't age such as movies and pre-recorded entertainment may be best moved by "data mules," vehicles or drones that can carry huge amounts of information and transmit them rapidly over short distances at high frequencies to digital mailboxes in rural areas. Imagine a flying NetFlix cache drone that wirelessly "drops off" the movie you want to watch tonight. Perhaps the US Postal Service will in addition to delivering physical mail also pickup and deliver e-mail and e-packages when they stop at your mailbox. (Or maybe even just drive by your mail box.) Perhaps Amazon deliveries will be the first data mules given their tech orientation. Perhaps all public safety vehicles will become satellite-connected mobile phone towers able to boost cellular or 5G capacity in the emergency or disaster areas to which the police respond. And perhaps they will also provide the time slot coordination to make the frequencies carry more traffic.

One interesting data mule capability is the ZeroG.network application developed by students at the University of Utah. It can relay tens of thousands of short messages to other smart phones running the same application even if an earthquake severs fiber optic links or a hurricane takes out backbone links connecting a community to the rest of the Internet. If even one of the participating phones physically transports out of disaster area, it carries with it all of the messages it holds. That smart phone or another one may bring back responses to those messages when brought back close enough to a cloud of ZeroG.network users. Of course, the same app works well in wilderness areas where there was no infrastructure to begin with; the lack of manmade infrastructure gives the smart phone radios extraordinary line-of-sight capability to other ZeroG.network phones.

And there is more to come.

In the United States, the Defense Advanced Research Projects Agency (DARPA) has been funding research into spectrum utilization techniques that are robust even in the face of adversarial uses of the same spectrum. This work may result in new technologies that allow spectrum to be more fully utilized even among mutually distrusting parties. No open access coordinator needed.
When these techniques are combined with phased array antennas, massive MIMO, time slot coordination, and innovation-friendly regulation, this paper may look old-fashioned in one short decade.

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