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Major Goals: This proposal requested funding to support a workshop on the topic of terahertz wireless communications, to be hosted by Brown University in the late spring of 2018. The purpose of this workshop is to identify current trends, challenges, and opportunities in the research and development of wireless communications systems that operate at frequencies above 95 GHz. Funds were used to cover the costs of travel for invited speakers, both from the US and overseas, as well as workshop logistics. The results of this workshop were summarized in a report.

Accomplishments: See uploaded Final Report

Training Opportunities: Nothing to Report

Results Dissemination: The final report was disseminated to all workshop participants.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

Terahertz Wireless Communications Workshop

Executive Summary: On October 9-11, 2018, Brown University hosted an international workshop on the topic of terahertz wireless communications. This event involved many of the world's leaders in this research field, including experts in sources, detectors, signal processing components, channel characteristics, and network architectures. The goal of this workshop was to identify the key research challenges, which would enable the realization of terahertz wireless systems. The workshop breakout sessions were organized around four theme areas: electronics-based sources and systems; photonics-based sources and systems; networks, architecture, and protocols; and external devices. Each of these groups discussed various aspects of the problem, identifying specific basic research challenges. These include challenges at both the physical layer and MAC layer. At the PHY layer, the basic research needs involve everything from determining the ultimate limits of source and detector performance to the arbitrary manipulation of generated wave fronts, polarization, and spectral content. At higher layers, research is needed to achieve orders-of-magnitude improvement in sychronization, as well as network discovery, routing, and access in a highly directional network where there is no omnidirectional control broadcast signal. Preserving network security will also require basic research, to determine the optimal strategy for spread-spectrum signaling in covert directional networks with deterministic dispersive characteristics.

The workshop participants noted that some of the basic research challenges described in this document are very generally applicable to all (or nearly all) of the envisioned use cases, whereas others apply more specifically to a subset of these scenarios. For example, in some uses, such as for backhaul or for high-rate data transfer in data centers, one may not need to enable mobility, as both ends of the link would be stationary. In these situations, only a limited degree of beam steering may be required for compensating small fluctuations due to atmospheric turbulence. However, in other situations, rapid and wide-angle beam steering will be required to allow for mobile clients. In another example, the envisioned range requirements can vary from centimeters (for rack-to-rack links or inside the case of a single ultra-high-definition display) to kilometers or more (for links between satellites or between aircraft in flight). Obviously, this variation in form factor has a dramatic impact on the optimal architecture for PHY layer components as well as networking protocols. Nevertheless, in all situations considered at the workshop, it was clear that the basic research challenges will all require a multi-disciplinary approach. No lone research group has the necessary breadth of expertise to tackle the many basic research problems discussed below.

Background: In the late 1980's, THz research took a major step forward with the development of laser-based technologies for generation and detection of THz signals. The emergence of this optics-based approach dramatically lowered the bar for THz measurements for many researchers. Yet, compared to integrated circuits, these optical systems are bulky and expensive. As a result of the unavailability of low-cost, portable, efficient technologies, the THz spectrum, while promising a wide range of applications in sensing, imaging and communication, has not yet lived up to that promise.

Over the last decade, there has been a significant surge of progress in enabling integrated, compact and efficient THz technology that has the true promise to close the 'THz gap' in meaningful ways. This progress is a result of a concerted effort stretching across a wide range of platforms including solid-state and photonic devices, heterogenous integration and system demonstrations. Importantly, much of the recent effort has been dedicated to exploiting techniques compatible with (or realized in) solid state semiconductor technology (III-V and silicon-based) that can operate at room temperature and be manufactured at a low cost, exploiting economies of scale. This is a critical departure from the focus on the search for the ‘perfect’ THz device, and towards a more holistic approach for realizing new system-level properties that can enable versatile THz systems. Such versatility is often required for advanced applications, and is generally lacking in many current non-integrated THz platforms.

As a result of this recent progress (as well as other developments, such as the looming roll-out of commercial 5G systems which will include a millimeter-wave broadcast standard), interest in THz communication systems has skyrocketed in the last few years. Key advantages include the promise of virtually limitless bandwidth and the presumed covert nature of communication links, in comparison with conventional broadcasts at lower frequencies. Yet, it is clear that much work needs to be done in order to realize functional systems that employ radiation above 100 GHz for communications. Advances are required in sources and detectors, but also in passive and active components for manipulating THz signals. New protocols will be needed for establishing a link using highly directional broadcasts, and for avoiding the effects of blockage and for mitigating the variations due to changing weather conditions. New methods must be developed for spread-spectrum management, both for optimizing the efficiency of data transfer and for maintaining covert operations. These and other research challenges will require a diverse set of skills and expertise, more than can be found in any one research group, either in the US or abroad.

As a final preliminary point, the workshop participants all noted that research on terahertz science and technology in the US now lags behind the pace of research in this field in many other nations. This state of affairs is exemplified by the lack of any US participation in the development of the IEEE channelization standard for the range 252-321 GHz. This standards document, developed over the course of several years by researchers from Europe and Asia, will be up for consideration for adoption as a global standard at WRC2019 in Geneva. It seems that it would be important for the US, long recognized as the global leader in wireless technologies, to avoid falling further behind in the frontier of wireless research.

Basic Research challenges: Wireless communication systems are often described using an abstraction which distinguishes the hardware components (the physical layer) from the signal processing and algorithms which implement protocols for managing data flow, detecting and correcting transmission errors, and optimizing spectrum usage (the media access control (MAC) layer). It is natural, therefore, to separate the research tasks into these two categories. However, when the physics of the transmission channel changes very dramatically (as is the case in the transition from microwave to terahertz links), it becomes necessary to adopt a more holistic viewpoint. New physical-layer architectures, which are limited by material properties, atmospheric losses, or the physics of beam propagation, will have major implications for the design of new MAC layer protocols. These can present both new challenges and new opportunities for the implementation and optimization of network services. Therefore, although most of the research performed to date has focused primarily on the development of components or other hardware (and, to a lesser extent, on the development of new protocols), it is clear that future advances will require a merger of these two sub-fields. Progress in device and sub-systems must be informed by the possibilities and limitations of signal processing; similarly, new approaches to implementing routing, discovery, and other network protocols must be aware of both current and future limits of source and detector technology.

This situation demands a highly collaborative and multi-disciplinary approach to the problem. Expertise is needed in the physics of propagation and material properties at terahertz frequencies, network theory, circuit design, and packaging. Meaningful progress will require a coordinated research team. With this caveat in mind, it is nevertheless still possible to roughly group the various research needs in categories.

Sources and Detectors: For nearly any of the envisioned uses of terahertz wireless systems, one of the key questions involves the nature of the source of radiation. There are numerous methods currently in use for generating THz signals, with ongoing advances in many areas. For any given application, it is often unclear which is the best choice. Part of the challenge stems from the fact that there are numerous different important parameters that can be used to characterize source performance. For example, it is commonly assumed that photonic approaches offer superior modulation performance (due to their ability to exploit a mature existing technology developed for fiber optic systems), but that they generate less power in the THz beam (due to the inefficiency of frequency conversion processes from the infrared). Yet, these assumptions may not be equally valid at all frequencies throughout the 100-500 GHz range. In the realm of photonics-based sources, it may be possible to build phase-coherent arrays of emitters and receivers, and to use such an approach to synthesize high-power and controllable beams. Optical frequency combs may prove valuable for synchronization. Yet, the fundamental limits of optical-to-THz conversion are not well understood, nor is it easy to quantify the performance of existing devices. Research which addresses these basic questions will have impact that spans the entire scope of terahertz networking.

To emphasize the need for basic research, we note that neither the fundamental limits for optical or electronic frequency conversion are known. Indeed, there is not even any widespread agreement on the appropriate metrics to use for such comparisons. Moreover, whether it is better to perform various signal processing operations (e.g., modulation, multiplexing, amplification) in the rf or optical domain remain important open questions. Comparisons of phase noise performance, frequency switching speed, or sychronization implemented using rf and optical techniques have not been considered. All of these observations also apply equally well to detection. Indeed, few research labs in the world have the equipment that would be necessary for a quantitative side-by-side comparison.

Generalized Beam Forming: Regardless of the approach used to generate or detect THz signals, one clearly identified challenge involves the need for high-speed and versatile control of the property of these THz signals in the far field. This goes beyond the customary definition of beam forming or MIMO processing, in which one typically considers only the possibility of spatial control of a wave front. In the terahertz regime, spatial control will clearly be critical for many envisioned applications; however, it is also easy to imagine that one could require control of other variables, such as polarization (which may need to vary across the wave front) or spectral content (which, again, may need to be different for different segments of a wave front). It is possible to envision such arbitrary waveform engineering, with high-speed reconfigurability and small form factor, because of the small wavelength, and also the possibility of creating arrays of sub-wavelength elements. Ideas such as programmable metasurfaces may provide a valuable new paradigm for either directly generating a tailored terahertz signal or for manipulating a signal externally to the source. The question of whether this processing should be accomplished via analog or digital multiplexing is an open one, depending on many factors. As the basic research necessary to enable such all-encompassing control of electromagnetic radiation has not been attempted, the ultimate limits of this control are not understood.

In the context of manipulating THz signals, many device architectures and functionalities have been explored. Some of these external devices may prove useful in terms of their versatility (i.e., they are, in general, agnostic with respect to the nature of the source and detector), as well as due to considerations such as power consumption and flexibility in system integration. For example, frequency multiplexing has been demonstrated in a passive waveguide-based element; it is not clear if this can be generalized to an active element which could implement dynamic frequency allocation. Devices such as isolators and circulators have only been demonstrated in bulk optical form, as passive components. Filters with high Q factor and low out-of-band losses are rare in the THz range; a resonator with a Q factor of 1000 is remarkable in this frequency range (as contrasted with much higher Q values that are routinely achieved both in the RF domain and in optics). A tunable and reconfigurable filter would be extremely valuable, but few such demonstrations exist. The limits of what can realistically be achieved, using either conventional materials or metamaterials, in free space or by exploiting guided waves, are not known. These open questions demand basic research into both traditional and novel methods for signal manipulation and control.

Synchronization and Signal Processing: The possibility for electronic control of radiating elements on a sub-wavelength scale raises additional intriguing possibilities. The idea of software-defined distributed emitter (or receiver) architectures opens the possibility for analog signal processing at the radiating surface, which could considerably relieve the DSP burden. The optimal design for such software-defined surfaces remains an open question, but this concept could have a dramatic impact on system functionality. Possible examples include the idea of pushing signal processing beyond f_{max} through the use of active antenna structures, and the combination of communication and sensing tasks in a single sensor. One may consider whether the conventional block-diagram paradigm, with an array of passive antennas coupled to active integrated elements, should be reconsidered from scratch.

Another key challenge for any communication system is that of synchronization. State-of-the-art systems achieve nanosecond-level synchronization across multiple nodes, including mobile elements. Dramatic (e.g., factor of 1000) improvements are required, to enable a wide range of new system architectures, including massive synchronized arrays, distributed beam forming, and low overhead for training and location in high-rate links. This will also have an impact on security, as eavesdroppers would not readily be able to synchronize with a secure link. The ultimate limits on the ability to synchronize, across both fixed and mobile networks, are not known. This is in part because the challenge is so distinct from that faced in traditional networks at lower frequencies, where one never encounters the idea of having an array of, e.g., MIMO antennas, integrated on a single chip that is larger than the free-space wavelength.

Network Protocols: The implementation of networks, particularly in the case where one or more of the network nodes is mobile, represents another significant set of challenges. At lower frequencies, an omnidirectional broadcast signal is a core building block of all wireless networks, providing a common channel for routing, access, and discovery. At terahertz frequencies, some alternative coordination mechanism will be required. It will need to operate reliably and with low latency, as well as (in some cases) covertly. Moreover, one can anticipate that the links in these networks will be bursty and highly unstable. Stochastic models to describe the timescale of variations remain at a rudimentary level of development for frequencies above 100 GHz. Such models will need to capture not only the impact of mobility, but also issues such as atmospheric effects, weather, and typical blockage scenarios. Channel monitoring should be location-aware, and could be aided by sensors at other frequencies (either RF or optical, or both) to enhance outage prediction capabilities. Such out-of-band information can help in the initial link acquisition and for adaptation in the presence of blockage.

For multi-stream multi-user networks, the limits imposed by interference are not yet known. As with many of the considerations discussed here, these are completely distinct from the issues of interference faced by traditional omnidirectional broadcasting networks at lower frequencies. To avoid interference between mobile network nodes, or interference with other services such as passive earth sensing or radio astronomy, consideration must be given to the design of radiating antennas with very low sidelobes. Experiments to simulate high spatial density of links will help to clarify the ultimate limits of such networks. Lastly, issues of spectrum sharing and resource allocation will be far more complex at these high frequencies. One cannot assume that all of the allocated THz spectrum resources will be available at all times. Spectrum will be constrained, not only by policy considerations and coexistence with environmental sensing or other passive services, but also by the dynamic and lossy nature of the channel. The basic research in these areas will need to proceed hand in hand with the development of spectrum policies, efforts which are only now just getting underway in the US (but which have already progressed significantly in global forums such as ITU).

Network Security: Given that enhanced security in wireless communications remain a fundamental advantage for high-frequency links, issues related to security are also of high priority. It has often been noted that narrower broadcasts will result in more secure links. Yet, this issue has only just recently begun to be explored in any depth. Moreover, the impact of beam forming on security, while well established at lower frequencies, remains an unexplored topic at higher frequencies. Particularly in cases where mobility is a requirement, the need for electronic beam steering may not be compatible with the idea of secure transmissions, depending on the detailed capabilities of the beam forming components. Basic research is required to address this question, involving expertise in both the capabilities of current (and future) beam forming components and the use of beam forming for secure transmissions.

Other issues also become more complex at higher frequencies. For example, at lower frequencies, spread-spectrum signaling and frequency-hopping are well-known methods for improving LPD/LPI performance. In the THz range, where the spectrum is much broader, the question of how best to use these capabilities for secure communications remains unanswered. For example, spectral bands are broad, but may be very dispersive for reasons that are quite different from the conventional multi-path dispersion encountered at lower frequencies. Strong dispersive effects can be observed even in a SISO line-of-sight link without multipath effects, if the carrier frequency is close to a molecular absorption line. Unlike at lower frequencies, these dispersive effects are deterministic, due only to the physics of molecular absorption, not arising from the randomness of multiple scattering. The effects of these considerations on spread-spectrum broadcasts, and in particular on LPD/LPI, are not known. Even the fundamental issue of network discovery and formation poses a challenge, both because of the lack of an omnidirectional overhearing broadcast channel (as noted above) and because of the need for covert operations. Ultimately, it would be desirable to enable a multi-hop mobile network without the need to broadcast network topology information. This will require a rethinking of the traditional routing paradigm, taking into account the fact that links are likely to be unstable and lossy. It remains unclear how to exploit spread-spectrum signaling in a scalable fashion across a multi-node or multi-hop network, and what security improvements can realistically be achieved. This set of basic research questions will require expertise in both wireless network security and the properties of terahertz channels, a combination that is not found in any single research group worldwide. This once again emphasizes the need for a multi-disciplinary and holistic approach to the basic research needs for terahertz wireless systems, a perspective that has so far been lacking in US research efforts.

Authored on behalf of all participants:

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Appendix I

The above discussion of basic research challenges identified by the workshop participants represents a distillation of many hours of discussions. In this appendix, we present the raw data – the specific research questions as written by the participants in each of the four break-out sessions. These discussion points were assembled with input from all workshop participants, and reviewed at the final session on Oct. 11th, prior to the closing of the workshop.

Break-out Session A: Solid-state sources and systems (Chair: Kaushik Sengupta)

1. What is the limit of spatial and temporal control of THz fields across a dispersive THz spectrum, and how dow we achieve the limits of arbitrary and dynamic control in a scalable fashion?
    a. One idea: to extend the concept of programmable metasurfaces that can allow multi-frequency beam shaping, notch and maxima control, polarization control, with high switching speed and low loss.
2. How do we process THz signals (and reject jamming) optimally, across distributed and dispersive spectral bands
    a. One idea: to investigate software-defined/programmable THz architectures that can process signals in a spatially and frequency-selective fashion
    b. What is the optimal electromagnetic interface? Should we re-think how we partition systems into antenna & processing blocks?
    c. Are there architectures that can allow spectral and spatial sensing and comm simultaneously?
    d. What are the fundamental limits of signal processing above f_{max}?
3. Are there inverse design approaches to THz electronic components and systems?
4. What are the limits of synchronization of moving nodes in a complex THz network?
    a. Nanosecond synchronization is the state of the art; picosecond level would allow a wide range of new capabilities (e.g., distributed beam forming, massive arrays)
    b. Would require low overhead for training in high speed network
    c. Can be important for security, as eavesdropper would not have the tools to achieve synchronization with the network.
5. What are the limits of spreading signals across selected bands in the THz range for security? How does this affect LPD/LPI? How scalable is this idea?
6. What are the limits for direct continuous-wave THz generation in a given form factor? What materials and devices can approach these limits?
    a. Interest in new materials (e.g., 2D materials), heterogeneous integration
7. What are the limits of frequency stability and phase noise of THz sources? Which is better, a mode-locked THz source or a phase-locked rf-multiplied source? Are there self-referencing techniques to cancel phase noise that are effective in the THz range?

Break-out Session B: Photonics-based sources and systems (Chair: Guillaume Ducournau)

1. What are the fundamental limits for optical-to-THz power conversion, frequency tunability, and phase stability? How do they depend on wavelength, material choices?

2. Could one build a (scalable) coherent array of photonic emitters / detectors for phase & amplitude control, to enable synthesis of directionally controlled high-power multi-frequency THz signals?
3. What are the fundamental limits to optically mediated THz mixing and detection, as measured by metrics such as NEP, noise figure, conversion efficiency, within an appropriate bandwidth for communication? More generally, what is the achievable SNR for a specific architecture?
4. Is it better to do the following in the optical domain or the THz domain? Synchronization, modulation, phase & amplitude control, polarization control, multiplexing, interconnection, amplification – and why? What metrics determine the answers, in each case?

Break-out Session C: Networks, architecture, and protocols (Chair: Edward Knightly)

1. Data plane:
    a. Understanding the channel: Stochastic models to capture the timescales of variation
    b. Impact of mobility, vibrations, atmospheric effects, etc.
    c. Link design: flexible waveform design for THz channel (example: OAM)
    d. Covert links to avoid eavesdropping (mechanisms for suppression of side lobes)
    e. Link acquisition and adaptation: beam acquisition for mobile nodes (enabling high gain wide beams to aid search)
    f. Channel precition including outage prediction, location-aware and sensor aided
    g. How to implement beam shaping
    h. Realizing synchronization in time, frequency, and phase
    i. Multi-stream, multi-user networks: Understanding interference, limits of high spatial density
    j. MAC control for unstable but high rate channels: Buffered and bursty comm links, require understanding of time scales, and synchronization.
2. Control plane:
    a. Omnidirectional (overhearing) broadcast is a core building block of wireless networks, for conveying control information (Routing, channel access, discovery). How does a THz network do this? (Coordination mechanism should be covert, timely/low latency, reliable, resilient).
    b. We cannot consider all THz spectrum available all the time. How do we enable dynamic spectrum sharing? Requires coordinated spectrum sensing, with constraints imposed by policy considerations, coexistence with environmental sensing & radar.
    c. Network formation and discovery: how do we covertly search for neighbors? Does this require beam width control? How do we enable mobile multi-hop networks without infrastructure? We cannot broadcast topology information (we may not even know it). This requires us to rethink the conventional routing paradigm from scratch. Is this step computation-limited or overhead/rate limited?

Break-out Session D: External devices (Chair: Daniel Mittleman)

1. To what extent can we control the spatial and temporal characteristics (amplitude, phase, polarization, directionality, etc.) of a radiated multi-frequency THz wave front?
    a. Impact on link discovery, covertness, spectrum sharing / interference, multiplexing, and more
2. What prevents us from making high Q devices for terahertz signals? What are the fundamental limits on the Q of a filter in this range?
    a. Narrow bandwidth, reconfigurable, low-loss; the THz field is orders of magnitude behind what can be done at rf frequencies in this. Is that a fundamental limit?
3. How do we design materials (or metamaterials) to approach the fundamental limits on functionality?
    a. To enable ultra-low-loss waveguides & interconnects; large and ultrafast nonlinearities for frequency conversion; broadband polarization control; impedance-matching interfaces
4. How do we optimally encode data in an ultra-broad THz frequency band which is discontinuous, lossy, and dispersive (due to, e.g., molecular resonances)?
    a. Implications for LPD/LPI? Implications for data rate, range, single vs. multi-user scenarios?
5. How do we achieve synchronization on a large scale of many elements? TX, RX, or external devices (e.g., modulator arrays)
    a. Power consumption, aperture size/form factor trade-offs
6. Is it possible to design a THz software-defined radio? If so, what components and architectures are required? (e.g., ultra-narrow filters? ultra-high speed ADC?)
    a. Given what we can do, what are realistic use cases enabled by this?

Appendix II

Participants from academic institutions:

1. Aydin Babakhani, UCLA
2. Hou-Tong Chen, Los Alamos
3. Alan Davy, TSSG Waterford
4. Guillaume Ducournau, University of Lille
5. John Federici, New Jersey Institute of Technology
6. Al Gasiewski, University of Colorado Boulder
7. Iwao Hosako, NICT Tokyo
8. Josep Jornet, University at Buffalo
9. Edward Knightly, Rice University
10. Daniel Mittleman, Brown University (host)
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12. Ullrich Pfeiffer, University of Wuppertal
13. Christopher Rose, Brown University
14. Kaushik Sengupta, Princeton University
15. Andreas Stohr, University of Duisburg Essen
16. Edward Wasige, University of Glasgow

Participants from US government:

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2. Alan Cook, NRL
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7. Joe Qiu, ARO