This is a reprint of the original article published in Society of Photo-Optical Instrumentation Engineers and is being reprinted here in FERMAT with permission from SPIE.

Multiband, Multiservice, Sensing: Metamaterials Myth and Reality

Dr. Mohsen Kavehrad
W.L. Weiss Chair professor, Electrical Engineering Department
229 EE-WEST
The Pennsylvania State University
University Park, PA. - 16802
Phone: (814) 865-7179
E-mail: mkavehrad@psu.edu

ABSTRACT - Demands by the communications industry for greater bandwidth push the capability of conventional wireless technology. Part of the Radio Spectrum that is suitable for mobility is very limited. Higher frequency waves above 30 GHz tend to travel only a few miles or less and generally do not penetrate solid materials very well.

Unmanned Aerial System applications require electronic scanning antenna capabilities, in challenging environmental conditions, over very large bandwidths. In addition to that, it is desirable to have as much reduction as possible in size, weight, power and cost.

Metamaterials are recently being introduced by periodic repetition of some inclusions in a host medium, which may be described as effective media characterized by a set of equivalent constitutive parameters. Self-similarity in creating periodic structures is the basis of building volume or 2D holographic components. The latter does more than periodic repeats. Similar, but more advanced concepts (fractal in nature) are used to model phase screens used in modeling the atmospheric turbulence.

Unfortunately, metamaterials (MTMs) are anisotropic (direction-dependent) and this makes their application limited in terms of use as antennas for mobile platforms. However, conceptually, controlled-anisotropy can be applied to make phased-arrays, beam-forming, and beam scanning. This issue then begs the question of cost comparison with conventional materials that can be found in nature, e.g., low-cost optics lenses, or conventional RF scanning antennas.

As for lensing and fixed platform imaging, the story is very different, as super-lens is expected to be a byproduct.

Nevertheless, even if metamaterials become readily available, the atmosphere around the globe cannot be replaced. Neither, broadband wireless connectivity to a mobile can be achieved via fiber optics.

This paper, presents a Hybrid radio-frequency (RF) and Wireless Optical solution to provide adaptive sensing in an opportunistic fashion, with or without metamaterials. A byproduct of the latter will be broadband and reliable global connectivity.

Broadband Access Communication Technologies VIII, edited by Benjamin B. Dingel, Katsutoshi Tsukamoto,
Proc. of SPIE Vol. 9007, 90070I · © 2014 SPIE · CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2044094

1. Introduction

With the increasing popularity of multimedia services supplied over the cellular radio frequency networks [1], data services such as web browsing, audio and video on demand, it is for sure only a matter of time before users will face extreme congestion while trying to connect to avail themselves of these aforementioned services. Advances in displays, battery technology and processing power have made it possible for users to afford and carry around smart phones and tablets. And so as we are entering a new era of always on connectivity, the expectation from users for not only ubiquitous but also seamless voice and video services presents a significant challenge for today's telecommunications systems. The prospects for the delivery of such multimedia services to these users are crucially dependent on the development of low-cost physical layer delivery mechanisms [2]. It is a known fact that the electromagnetic spectrum has become extremely crowded [3]. The wireless handheld devices require ever-increasing bandwidth, and along with that, explosive growth in inter-device wireless communications is already creating huge demands on spectrum resources which can be resolved only by near zero-sum allocation decisions. We need 'new spectrum,' and we also need mechanisms to address the 'tragedy of the commons' problem with the allocated spectrum, that unless some sort of regulation is implemented, the rational strategy for individual users never produces Pareto optimality among permitted users [4]. The tragedy of the commons is a dilemma arising from the situation in which multiple individuals, acting independently and rationally, consulting their own self-interest, will ultimately deplete a shared limited resource, even when it is clear that it is not in anyone's long-term interest for this to happen [5].

There is a valid question here to ask. Is the bandwidth between 1.9 GHz and 3.00 GHz suitable for outdoor cellular mobile? If so, why does not FCC release that to the wireless/mobile industry in order to ease the spectrum crunch problem? This question is one of those questions that have a complex answer. Of course, 1.9 GHz is not as good as 890 MHz for outdoor cellular mobile, but is useful and has served additional users. As frequency increases, the path loss increases perhaps as frequency squared to frequency to some higher power, depending on environment. You could not tell the difference between 1.9 GHz and say: 2.2 GHz because the difference would be small and there would be large statistical variations. The difference between 1.9 GHz and 3.00 GHz would be noticeable, but would be less than between 890 MHz and 1.9 GHz since the ratio is less. However, 3.00 GHz would have somewhat more path loss than 1.9 GHz. There is no cliff as frequency increases; it just becomes more difficult gradually to deliver a high quality-of-service over a non-line-of-sight (Non-LoS) path. This issue becomes less important as the base station spacing has decreased to increase system capacity. Decrease spacing by factor of two and capacity increases by factor of four. Close spaced base stations need less link margin to overcome path loss so the increased path loss with frequency tends to be offset by the closer spacing. Allocating more bandwidth to the cellular designated spectrum would help a little with the spectrum crowding, but probably not enough to take care of the major issue. Even if you had twice the bandwidth available, that is a small help. The problem is that cellular technology, both cell phones and infrastructure, has moved to video, pictures, and web browsing, all of which require orders of magnitude more bandwidth than voice. Thus, the "capacity" issue is orders of magnitude worse than voice and allocating twice or so more spectrum is only of marginal help. Decreasing base station spacing (increasing base station density) is a better way to provide more capacity and that is what has been done for the last 20+ years.

The wireless industry is talking about femto-cells and high-capacity back-hauling. They predict the volume of wireless data will exceed that of wired data by 2015. The question is how this enormous data capacity will be realized, while meeting customer quality-of-service expectations and operators' requirements for cost-effective service delivery. The answer is a significant ramping up of small cell deployment. But is that realistic? What about the cost of cell towers and radio / switching equipment that will proportionally be higher? Perhaps a better resolution of the issue would be to stop pretending that spectrum is free and start charging for use by how much bandwidth is consumed. Unfortunately, data users tend to think bandwidth should be free and waste it with lots of protocol overhead and with transmitting video, pictures, and web things that users would not really be willing to pay for if they had to pay for the bandwidth wasted at the same rate as they pay for bandwidth for voice.

At the moment, no one wants to pay for the mass amount of data and no company appears willing to charge for it. The enormous amount of data results because it is way under paid for, not because there is a large amount of data users are willing to pay for. This is not a realistic situation [6]. By charging for the band, the data users are encouraged to use the bands allocated for "Wi-Fi" type of service for indoor wireless LAN (WLAN) or IEEE802.11 type. There are 3 main bands of operation for indoor WLAN, each with their own maximum data rate. These are 2.4 GHz, 5 GHz and 60 GHz. The 2.4 GHz band has the potential to suffer the most multiuser interference. The 60 GHz band is just emerging so it has little to no interference. Maximum data rate for each band is different. For the 2.4 GHz the maximum is set by 802.11n (something around 600 Mbps). For 5 GHz the maximum is set by 802.11ac (~ 1 Gbps). For 60 GHz the maximum is set by 802.11ad (~ 7 Gbps). Are these data rates an issue? Are these sufficient for today's users? The answer depends on what the user is trying to do.

In this paper, we will examine the possibility of using new materials and devices to help with designing more compact and focused wireless beams of RF and optical natured in order to address the wireless broadband transmission problems and ease accessing the limited and currently congested radio frequency spectrum. Next section focuses on the interaction of waves and materials. Section 3 discusses the hybrid RF and laser links. Finally, conclusions appear in the last section of this paper.

2. Wave propagation through Materials and Metamaterials

In [3], we demonstrated the limited use of cognitive radios and the idea of sharing the radio spectrum through detection and identification of less loaded parts of the frequency spectrum in a congested metropolitan area such as New York, Boston or Los Angeles, etc. Radio waves, visible light, infrared, ultraviolet, X-rays, and all the other parts of the electromagnetic spectrum are basically electromagnetic radiation, behaving differently in the materials, due to wavelength size. Only about 2 GHz of the lower microwave bands is useful for full wireless mobility due to low absorption and ability to reflect off the objects, thus providing a multiple paths channel between a transmitter and receiver communicating over the channel.

Unmanned Aerial System applications require electronic scanning antenna capabilities, in challenging environmental conditions, over very large bandwidths. In addition to that, it is desirable to have as much reduction as possible in size, weight, power and cost.
In a mobile transceiver operating in this band, antennas are the only components with physical limitations for miniaturization. Steerable antennas using focused beams are able to offer lots of spatial reuse of the same carrier frequency in order to increase capacity in a mobile cellular network that re-uses frequencies. Miniaturization of antennas is limited by physical bounds. Efficient usage of the form factor, effective enlargement of the aperture by coupling to nearby structures and excitation of free space regions, meandering current paths, or engineered (meta)-materials usage – all of these can lead to structures that are as compact as possible. Beyond this - there is only wizardry.
A material is just a collection of electric and magnetic dipoles. Homogenization allows this collection to be continuous. In other words, it is composed of discrete elements, which are either charged or non-charged particles. If an object (e.g., a single electron, atom, molecule, or particle) is illuminated by an electromagnetic (EM) wave, the interaction between the particle and the EM wave is observed as variations in the traveling EM wave. This interaction is governed by several variables, most prominently – but not limited to- particle size, wavelength and the relative refractive index of particle to the surrounding medium. This interaction is caused by the excitation of the electric and magnetic dipoles within the object; resulting in an oscillation and radiation of secondary EM waves in what is known as scattering, and/or to transform some part of incident energy into other forms of energy in what is known as absorption [7].
The interaction between particles and EM waves can be fully understood through Maxwell's equations that provide mathematically convenient forms to evaluate various aspects of the interaction process. From the electromagnetic point-of-view, an atom is just an electric or magnetic, polarizable dipole. Maxwell's equations do not "know" about atoms or molecules – all they "know' is magnetic and electric dipoles. We can use any object to create a dipole response, and use that object to form an engineered material.
Material response varies at different frequencies. This is determined by atomic structure and arrangement (10^{-10} m). One can alter a material's electromagnetic properties. A possible method is to introduce periodic features that are electrically small (sub-wavelength sized) over a given frequency range, that appear "atomic" at those frequencies.
The paths of light and other electromagnetic waves can be controlled by materials. The lenses in eye glasses or microscopes, for example, are nothing more than pieces of glass or plastic whose surfaces have been shaped in a particular way so as to achieve a desired optical function. Materials are used to form optical devices that operate across the electromagnetic spectrum, from radio waves to visible light.
Nature has provided us a rich palette of material properties from which to engineer useful optical devices. Yet, that palette is limited: chemical synthesis, the conventional approach to material development, has so far not enabled us to access the entire range of material properties that should be theoretically possible. But chemistry is not the only process by which we can create materials. As an alternative approach, we can artificially structure a material by assembling a collection of objects together. These objects serve to replace the atoms and molecules of a conventional material, the result being a composite structure that can have electromagnetic properties unlike any naturally occurring or chemically

synthesized material. Such composites have been termed *metamaterials*, because they have properties that extend beyond materials found, naturally [8].
New materials platform – metamaterials are engineered as multi-phase composite materials containing inclusions that often have tailored shapes, sizes, mutual arrangements and orientations. Such materials exhibit responses unparalleled to many types of wave excitations, including: Electromagnetic (transverse waves), acoustic (longitudinal waves) and seismic (transverse and longitudinal waves).
Metamaterials coined in 1990's [8] formed by periodic repetition of some inclusions in a host medium, which may be described as effective media characterized by a set of equivalent constitutive parameters. According to some researchers, any material composed of periodic, macroscopic structures so as to achieve a desired electromagnetic response can be referred to as a engineered-(meta)material, as shown in Fig.-1. Others prefer to restrict the term metamatetial to materials with electromagnetic properties not found in nature. Almost all agree the engineered-(meta)materials do not rely on chemical/atomic alterations. Periodic structures and self-similarity are the basis of building volume or 2D holographic components [9-10]. Similar concepts are used to model phase screens used in modeling the atmospheric turbulence [11]. These concepts have been recognized in some fields for decades. Engineered-(meta)materials are being designed and used in the microwave frequency regime, with possible extension of general concepts into infrared, as Plasmonics [8].

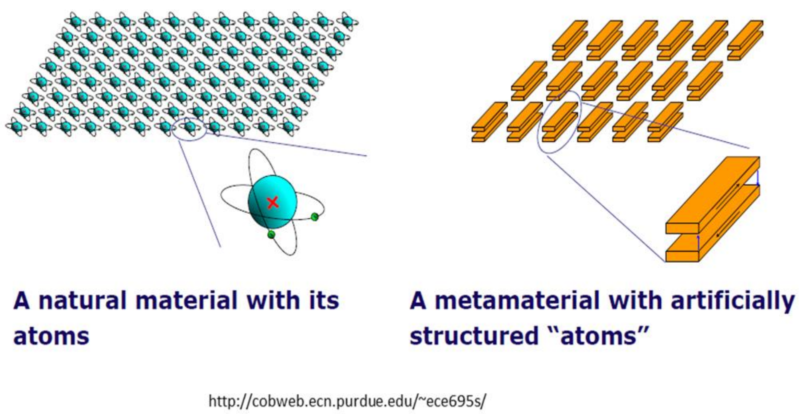

Figure-1. Natural materials versus engineered-(meta)materials.

Particles of various densities and properties are present throughout the atmosphere; their distribution varies according to altitude, weather conditions, geographical location and seasonal changes [12 - 16]. Thus, it is expected that when an EM wave, referred to as TM or TE modes, traverses between a transmitter and a receiver in the atmosphere, the detected wave will suffer from scattering and absorption (see Fig.-2).
Spherical particle-wave interaction is commonly known as the Mie theory or the Lorenz Mie theory, in recognition of G. Mie and L. Lorenz who independently developed the principles of electromagnetic plane wave scattering by a dielectric sphere. G. Mie developed the theory in an effort to understand the varied colors in absorption and scattering exhibited by small colloidal particles of gold suspended in water.

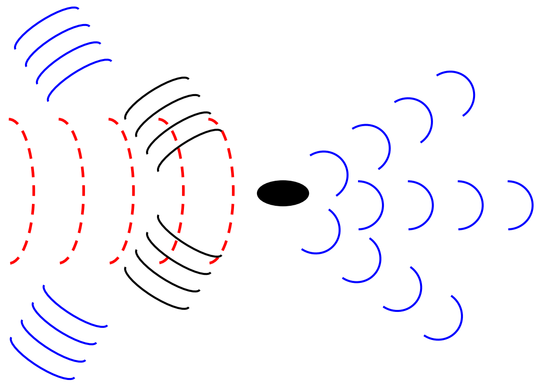

Figure – 2. Particle – Wave Interaction;
Dashed line: Incident wave Solid line: Scattered wave.

Again, the interaction between particles and EM waves can be fully understood through Maxwell's equations. Although it is usually assumed that the particles are spherical, many atmosphere borne particles are not spherical, but due to the random orientation of the particle in space, particles can be well approximated to be spherical with an average size [12]. Figure-3 illustrates the role of sub-wavelength sized particles and the properties of natural materials or engineered metamaterials.

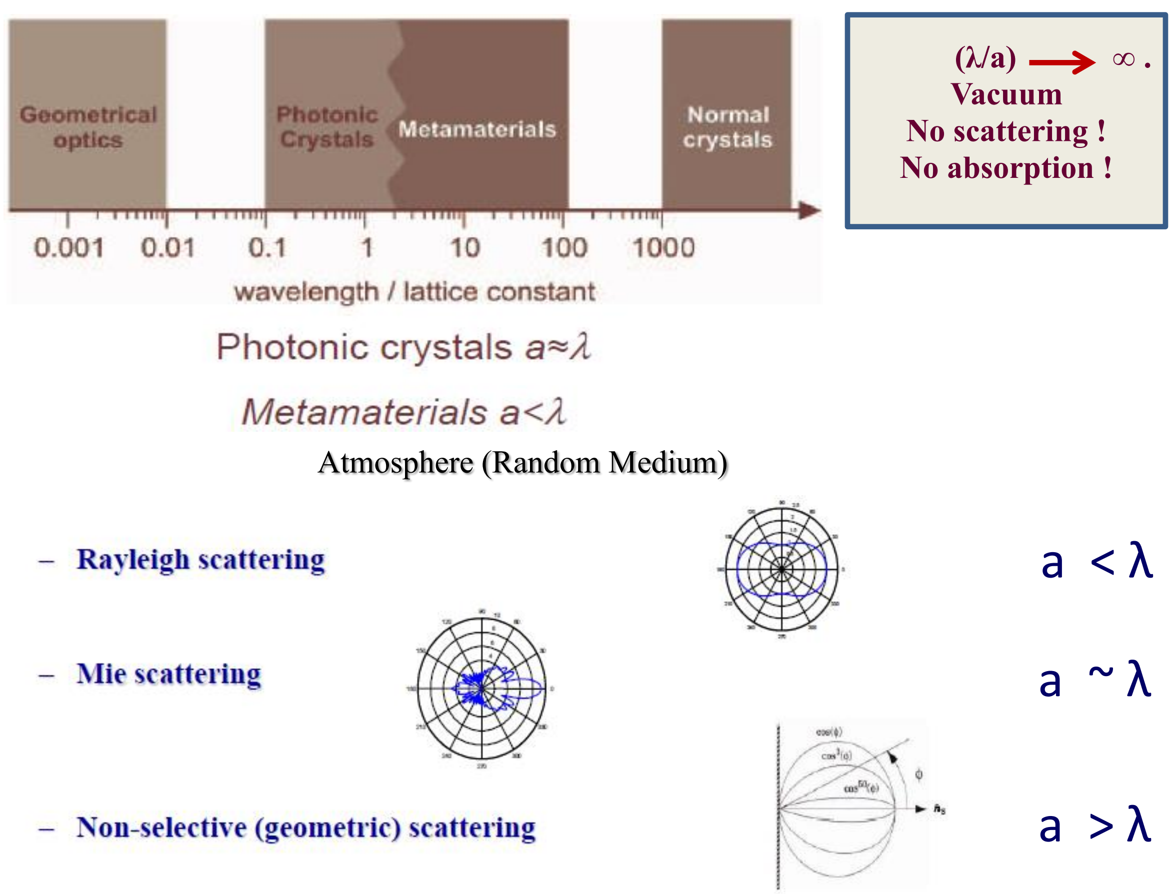

Figure – 3. Particle – Wave interaction in terms of sub-wavelength particle size (a) and EM wave's wavelength (λ).

In vacuum where the particle size a=0, there is no scattering, no absorption, given enough power to make up for a finite transmit/receive aperture antenna sizes, EM waves can propagate over very large distances carrying extremely broadband signals. If we reverse engineer vacuum, the next best place in terms of propagation distance is within normal crystals (e.g., silicon or glass fiber) where we can have vacuum-like transmissions with the possibility of launching nonlinear EM modes as Soliton which is a self-reinforcing (dispersion-free) solitary wave. For the ratio $(\lambda/a) \leq 100$, metamaterials start to introduce dispersion, thus spatial and frequency selectivity and filtering in space and frequency are observed. Photonic Crystals that exhibit bandgap nature are the extreme example, as (λ/a) approaches unity. In solid-state physics, a bandgap, also called an energy gap, is an energy range in a solid where no electron states can exist. These materials are known to be least relevant for applications where dispersion is not desirable, for example fiber optic transmissions.

Natural examples of what Photonic Crystals are similar to, in behavior, are peacock feathers, rain drops and butterfly wings that can produce different colors by changing the incidence or view angle with respect to visible light reflection on the object. In imaging, these are referred to as tip and tilt features. For the ranges of $(\lambda/a) \leq .01$, the geometric optics range starts where by adopting ray-tracing, propagation modeling can be performed. A parallel for these behaviors in atmosphere create the Rayleigh scattering (blue sky as seen in the atmosphere) and Mie scattering as light travels through cloud, fog, dust or smoke particles. Some explosives smoke, such as fog-oil, exhibits similar scattering of lightwaves.

In 1968, theoretical designs by the Russian scientist Dr. Victor Veselago predicted metamaterials act in exact opposite manner than natural materials (like negative refractive index) in a pioneering paper [17]. It took until 1999 that Sir John Pendry [18] introduced how to arrive at negative index materials engineered by inclusions of sub-wavelength elements in a substrate to produce such metamaterials. These engineered materials have unique properties not found in nature due to the arrangement and design of the constituents. Metamaterials are causal and dispersive and are called left-handed as they exhibit a negative group phase response resulting in wave vector to have an opposite direction compared to the energy propagation direction. These materials are transparent for propagation, but anisotropic in nature, so the direction dependence they exhibit makes these unsuitable for use in mobile platform antennas, unless a line-of-sight can be guaranteed. However, recent advancements in introduction of controlled-anisotropy have made it possible to produce frequency selective surfaces that provide tunability and thus scanning and steering features are possible over multiple narrow frequency ranges at a limited slow speed of scanning. The question is, if the anisotropy is controlled, can these materials then compete in cost with the cost of conventional materials. Again, line-of-sight between transmitter and receiver is necessary, due to polarized nature of propagation. These concepts have also resulted in transformational optics (cloaking) and the concept of perfect lens that is capable, in theory, to counter diffraction limit and the losses owing to evanescent fields.

3. Hybrid Wireless RF and Wireless Laser Link Transmissions

Even if engineered metamaterials become fully available and usable, the atmosphere remains as a random medium. Hence, we examine the properties of the atmosphere and the interaction with radio and light waves. In [19-24], we showed the anti-correlation of RF and optical waves as they propagate through the atmosphere. It is possible to exploit this in form of a multi-band, multi-service transmission links that through diversity reception can provide a ground-to-air vertical link capable of offering broadband transmissions in an opportunistic fashion. The central idea is to enable optical communications bandwidth without giving up RF reliability and "all-weather" performance.

Metamaterials can possibly help to make a nearly perfect lens antenna system available both in RF as well as in the infrared (IR) range. However, in a private e-mail exchange with Professor David R. Smith, recently [25], he states: *"The concepts of metamaterial optics are definitely revisiting some older concepts. For cases where you might want slow scan speeds, the use of LC resonators with metamaterials is rapidly maturing. Satellite communication products are being developed based on LC metamaterials, for example. Any of these concepts for perfect lenses would all need to address the fundamental problem of perfect lenses, which is that losses place a severe limitation on the sub-wavelength focus. I don't think I've seen an example yet where the perfect lens concept can compete with traditional engineering approaches, given the limitation of losses. Adding gain seems to be marginal in improving the situation for many reasons. The most encouraging work I've seen has made use of a nonlinear process (four wave mixing) at a metamaterial surface to generate effectively negative refracting waves. Since one can pump in as much power as desired, there might be some hope of achieving significant sub-wavelength focus. Otherwise, the inherent losses of metals are just too much, at nearly any wavelength. I should add the exception that guided wave structures appear somewhat more robust to losses and can exhibit pretty tight sub-wavelength features. If there is an application for such structures, then there might be a route through confined geometries".*

Fig.- 4 shows the path loss versus path length in a temperature-controlled indoor environment over a 10 meters range for a 60 GHz and a 1.7 GHz RF link [26]. The radiation pattern of the measurement RF antenna was narrow (3 dB beam-width 5 degrees) in the vertical plane and broad (90 degrees) in the horizontal plane. Over the same path in a similar environment, we measured zero dB loss on an infrared wireless laser link beam focused via a low-cost COTS lens [27].

The demonstrated success of wireless laser links has generated an intrigue to further expand their utilization in different environments, namely mobile environments, specifically for avionic applications where the wireless laser links can be used as ground-to-air and air-to-air links to provide broadband communications at rates far beyond rates achievable through conventional wireless RF systems.

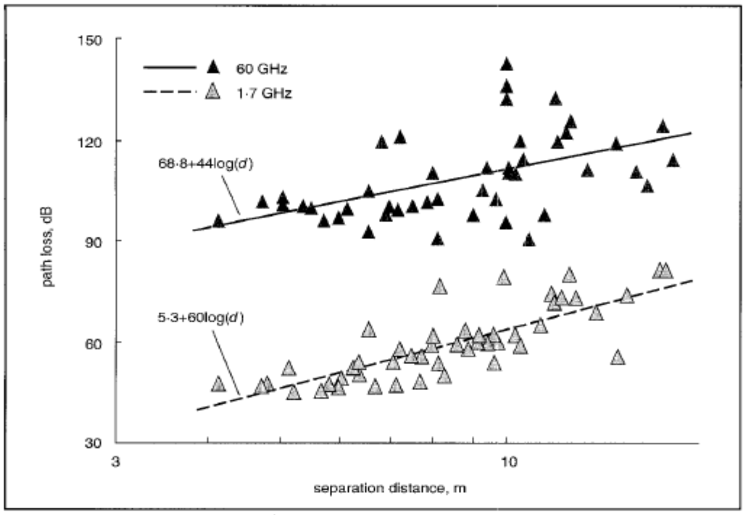

Figure-4 Path Loss versus Path Length at 1.7 GHz and 60 GHz.

The ability to use wireless laser links in airborne mobile environments would open the doors for many applications that can provide huge benefits to mankind; for example, unmanned air vehicles (UAVs) equipped with imaging devices and a broadband wireless link would be an extremely valuable tool for search and rescue efforts, by providing the ability to scan targeted areas in less time and relay high resolution images to control centers safely without the need to deploy teams in hazardous situations. In agriculture, similar UAVs can aid in sending real time high-fidelity information about crops, soil and environmental conditions thus helping in providing a more accurate control over production areas, thus maximizing production and minimizing losses. Additionally, the ability to provide broadband access to commercial planes can make universal connectivity a reality and finally for military applications, in addition to providing surveillance and imaging abilities, wireless laser links can help in creating a "network in the sky" that has the ability to adapt to the continuously changing demographics of the battle field creating a virtual bridge between the battle field and the operation centers relaying huge amounts of data providing the combatants, ground vehicles and operation centers with continuously updated data that have become a crucial element in today's battle field [19-21].

In this section, we consider feasibility of hybrid RF / Wireless Laser Link systems. Strictly speaking, such a system is different compared to typical Multi-Input-Multi-Output (MIMO) systems system due to the non-interfering nature of the two subsystems and the anti-correlation noted. Unlike the channel models for capacity evaluation and equalization, in order to analyze availability, we need to focus on the macroscopic fading factors rather than the microscopic factors. When constructing channel models for equalization, based on the assumption that the large-scale fading is slow varying and thus can be compensated by adaptive power adjustment, long-term attenuation effects are not included in the model. Nevertheless, when availability is considered, it is assumed that the maximal transmit power is limited by the power budget. Hence, if large-scale fading factors such as the path loss fluctuate significantly, the system will experience an outage.

In order to construct the channel model of a hybrid wireless link, we consider a system consisting of two line-of-sight subsystems: an RF and a wireless Laser Link subsystem. Due to the fact that the two subsystems operate on very distinctive frequencies, the overall channel can be modeled by combining channel models of the two subsystems. Because availability is most affected by weather-related fading factors, the RF channel model is constructed based on an integrated set of four link attenuation models that estimates margin losses due to rain, fog/cloud, atmospheric (water vapor and oxygen) attenuation and multipath effects. Likewise, the wireless Laser Link channel model considers mainly rain and fog attenuation. Considering that the Laser Link wavelength is 1550nm, gaseous attenuation can be neglected. Nevertheless, small-scale fading factor such as scintillation must be taken into account to complete the model. We presented a detailed availability model and analyses in [19-21].

For the atmospheric portion of the transmission path, airy-shaped beams show promise due to their self-bending properties [28]. Also, wide Field-of-View (FoV) optical antenna receivers have been designed and compared by our team [29-32]. The imaging wide FoV fly-eye receiver proposed in [32] and re-used in [33], were introduced in the context of MIMO systems and investigated in [29] in terms of link capacity in strong atmospheric turbulence conditions. We introduced another wide FoV optical antenna called the fish-eye receiver in [31]. This is also an imaging lens in a Single-Input-Single-Output (SISO) configuration. We compared its performance to the MIMO fly-eye antenna in [30] and showed the latter, in addition to providing a wide FoV, also offers MIMO gain, resulting in performance improvements.

4. Conclusions

In this paper, we covered a wide range of subjects with the objective of defining a road map to broadband and reliable global connectivity. The current congestion of mobile bands, the size limits antennas introduce in the lower microwave RF range beg for solutions that may be on the horizon by involving engineered-(meta)materials and employing a hybrid wireless RF and wireless laser link transmission connecting ground stations and mobile airborne platforms. Such system configurations improve the performance of remote sensing, be it for communications, imaging and/or navigations.

REFERENCE

1. “Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2009-2014” [Available Online]: http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.html.
2. M. Kavehrad, “Sustainable Energy-Efficient Wireless Applications Using Light”, IEEE Communications Magazine, pp. 66-73, December 2010.
3. M. Kavehrad, "Optical wireless applications: A solution to ease the wireless airwaves spectrum crunch," Invited paper - SPIE Photonics West, San Francisco, CA, February 2 - 7, 2013.
4. M.J. Osborne, and A. Rubenstein, 'A Course in Game Theory,' MIT Press, pp. 7, 1994.

5. G. Hardin, 'The Tragedy of the Commons', Science, Vol. 162 No. 3859, pp. 1243-1248, December 1968.
6. Private e-mail exchanges with Professor Donald C. Cox, Harald Trap Friis Professor of Engineering and a member of the Stanford University Electrical Engineering Faculty in Wireless Personal Communications; Cellular Mobile Radio; Wireless Data Networks; Signal Processing; Radio Propagation; Former Executive Director and Division Manager of Radio Research at Bellcore; Former Department Head, Supervisor, and Member of Technical Staff at Bell Laboratories. E-mail date: January 2013.
7. C. Bohren, D. Huffman , "Absorption and Scattering of Light by Small Particles," Wiley Interscience, New York, 1983.
8. D. R. Smith, W. J. Padilla, D. C. Vier, R. Shelby, S. C. Nemat-Nasser, N. Kroll and S. Schultz, "Left-handed metamaterials," in Photonic Crystals and Light Localization, ed. C. M. Soukoulis, Kluwer, Netherlands, 2000.
9. M.R. Pakravan, E. Simova, M. Kavehrad, "Holographic Diffusers for Indoor Infrared Communications Systems," Proceedings of GLOBECOM, London-England, Nov. 1996.
10. S. Jivkova, M. Kavehrad, "Indoor Wireless Infrared Local Access, Multi-Spot Diffusing with Computer Generated Holographic Beam-Splitter," Proceedings of IEEE ICC'99, Vancouver, CANADA, June 1999.
11. Z. Hajjarian, Jarir Fadlullah, M. Kavehrad, "Use of Markov Chain in Atmospheric Channel Modeling of Free Space Laser Communications," Proceedings of the IEEE MILCOM, San Diego, CA, November 2008.
12. F. Smith, "The Infrared & Electro-Optical Systems Handbook, Volume 2: Atmospheric Propagation of Radiation," SPIE Press, 1993.
13. V. De Hulst, "Light Scattering by Small Particles," Wiley, New York, 1957.
14. Karp et. al, "Optical Channels: Fibers, Clouds, Water and the Atmosphere," 1988.
15. R. M. Harrison, R. E. van Grieken, "Atmospheric Particles, Volume 5," Wiley, New York, 1998.
16. J. H. Seinfeld, S. N. Pandis, "Atmospheric Chemistry and Particles," Wiley Interscience, New York, 1998.
17. V. Veselago. "The electrodynamics of substances with simultaneously negative values of epsilon and mu," Soviet Physics Usp., Vol.-10, pp. 509-514, 1968.
18. J.B. Pendry, A.J. Holden, D.J. Robbins, and W.J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," IEEE Trans. on Microwave Theory and Techniques, Vol.-47, No.-11, pp. 2075-2084, November 1999.
19. H. Wu and M. Kavehrad, "Availability Evaluation of Ground-to-Air Hybrid FSO/RF Links," International Journal of Wireless Information Networks, Springer Science Publisher, Vol. 14, No. 1, pp.33-45, March 2007.
20. M. Kavehrad, S. Lee, S. M. Navidpour, "Fractal Transmission in a Hybrid RF and Wireless Optical Link: a Reliable Way to Beam Bandwidth in a 3D-Global Grid," Proceedings of SPIE Optics East, Boston, Mass., October 2006.
21. H. Wu, B. Hamzeh and M. Kavehrad, "Availability of Airborne Hybrid FSO/RF Links," SPIE Defense and Security Symposium, Orlando, Florida, March 28-April 1, 2005.

22. M. Kavehrad, "A New Diversity Technique for Interference-Limited Microwave Digital Radios," Canadian Conf. on Elect. and Computer Engineering, Ottawa, Ontario, September 1990.
23. M. Kavehrad, "A Hybrid Radio Model and its Performance in RF Interference Environments," Technical Memorandum, AT&T Bell Laboratories, April 1988.
24. M. Kavehrad, "Design and Performance Considerations for the Hybrid Atmospheric Optical/Digital Microwave Network Systems," Technical Memorandum, AT&T Bell Laboratories, December 1987.
25. Private e-mail exchanges with Professor David R. Smith, currently the William Bevan Professor of Electrical and Computer Engineering Department at Duke University and Director of the Center for Metamaterial and Integrated Plasmonics. E-mail date: August 2013.
26. P. F. M. Smulders and L. MI. Correia, "Characterization of propagation in 60 GHz radio channels," Electronics & Communication Engineering Journal, April 1997.
27. M. Kavehrad, M.I.S. Chowdhury, W. Zhang, "Combined CATV and Very High Speed Data Transmission over a 1550 nm Wavelength Indoor Optical Wireless Link," Proceedings of SPIE Photonics West - OPTO, San Francisco, CA, Feb. 2014.
28. Chunyi Chen, Huamin Yang, Mohsen Kavehrad, Zhou Zhou, "Propagation of radial Airy array beams through atmospheric Turbulence," Optics and Lasers in Engineering, Journal, available online (http://www.sciencedirect.com/science/article/pii/S0143816613002182#), July 2013.
29. Peng Deng, Mohsen Kavehrad, Zhiwen Liu, Zhou Zhou, and XiuHua Yuan, "Capacity of MIMO free space optical communications using multiple partially coherent beams propagation through non-Kolmogorov strong turbulence," Optics Express Journal, Vol. 21, Issue 13, pp. 15213-15229, July 2013.
30. P. Deng, M. Kavehrad, X. Yuan, "Comparing Wide Field-of-View Optical Receivers for Free Space Optical Communications," IEEE Photonics Society Summer Topical Conference – Optical Wireless Systems Applications, Seattle, July 2012.
31. Peng Deng, XiuHua Yuan, Mohsen Kavehrad, Ming Zhao, and YanAn Zeng, "Off-axis catadioptric fisheye wide field-of-view optical receiver for free space optical communications," Optical Engineering Journal, 51, 063002, DOI:10.1117/1.OE.51.6.063002, June 2012.
32. G. Yun, M. Kavehrad, "Spot Diffusing and Fly-Eye Receivers for Indoor Infrared Wireless Communications," Proceedings of IEEE Wireless Communications Conference, Vancouver, June 1992.
33. Z. Hajjarian, M. Kavehrad, and J. Fadlullah, "Spatially multiplexed multi-input-multi-output optical imaging system in a turbid, turbulent atmosphere," Applied Optics Vol. 49, No. 9, pp. 1528–1538, March 2010.