Remote Sensing and Estimation

RLE Group
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Self-Organizing Spectrum Allocation

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This program seeks to determine, as a function of link length relative to user density, approximate limits to the average communications rate (bits/second/Hz/user) that could be exchanged between pairs of wireless mobile users randomly distributed over a two-dimensional plane. Of primary interest is the dependence of those bit-rate limits upon protocols, numbers of antennas and data streams employed, and multipath characteristics. This year's effort focused on publication of prior work [1-2] and on development and analysis of multi-antenna protocols for wireless ad hoc network environments in which most links are single-hop.

A new protocol (Simultaneous Transmissions in Interference (STI-MAC)) was developed for ad hoc wireless networks. Its key advantage is efficient 'channel stuffing' that allows network nodes to use spatial, time, and frequency degrees of freedom more efficiently. The protocol: 1) facilitates use of multiple receiver antennas and minimum-mean-squared-error (MMSE) receivers that permit nearby network nodes to transmit simultaneously in the same band, 2) enables multiple transmit antennas to maximize power received by the target receiver, 3) uses a control channel orthogonal in time to the data channel, where nodes contend in order to participate on the data channel, and which is sufficiently broadband that its brief robustly coded packets also calibrate the link spectral characteristics, and 4) accommodates a protest scheme that helps prevent channel overloading.

Using Monte-Carlo simulations the protocol was analyzed for planar networks as a function of the number of transmitter-receiver pairs (up to 40), the numbers of transmit and receive antennas, the approximate number of in-band interferers closer (stronger) than the desired transmitter (the "link rank"), the transmit scheme, the distribution of requested data rates, and the offered load. Relative to the 802.11(n) (Wi-Fi) protocol, graduate student Danielle Hinton found gains in network throughput (bits/sec/Hz/network) of ~5X-30X for networks with 40 transmit-receiver pairs, rank-3 links, a link-length of 10 meters, and eight transmit and receive antennas, where the transmitter beamforms to its target receiver in its strongest target channel mode. The advantage is ~3X for 20 transmitter-receiver pairs, 10-meter link lengths of rank 1, four receive antennas, and a single transmit antenna. The advantage of STI-MAC increase significantly with link rank (interference levels) and network congestion.

Journal Papers

1. K. T. Herring, J. W. Holloway, D. H. Staelin, and D. W. Bliss, “Path loss characteristics of urban wireless channels,” *IEEE Transactions on Antennas and Propagation*, Vol. 58 (1), pp171-177 (2010).

2. S. Govindasamy, D. W. Bliss and D. H. Staelin, “Asymptotic Spectral Efficiency of Multi-antenna Links in Wireless Networks with Limited Tx CSI”, *IEEE Transactions on Information Theory*, in review, 2010.

Theses

1. Danielle A. Hinton, Protocols for multi-antenna ad-hoc wireless networking in interference environments, PhD thesis, Department of Electrical Engineering and Computer Science, August, 2010.

NPOESS Program Science Team Support

Sponsor
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Project Staff
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This program supports Lincoln Laboratory and NOAA Integrated Program Office efforts to develop a National Polar Orbiting Environmental Satellite System (NPOESS), with emphasis on the next generation Advanced Technology Microwave Spectrometer (ATMS) to be launched in the next few years, and retrieval of global precipitation using operational and future satellite instruments such as ATMS and the Microwave Imager/Sounder (MIS).

The scientific effort involved continued development and evaluation of improved satellite precipitation and hydrometeor path retrieval algorithms using millimeter-wave spectra. Portions of this effort were also separately supported by the NASA effort “Study of Millimeter-Wave Satellite Precipitation Retrieval Algorithms Using MM5 Simulations”. The four main efforts are summarized below and involved: 1) improvement of the correction for rain evaporation, 2) development of precipitation retrieval methods applicable to the U. S. Air Force Special Sensor Microwave Imager/Sounder (SSMIS) millimeter-wave conically-scanned imager sounder, 3) development of methods for estimating the accuracy of individual single-pixel retrievals of temperature, humidity, and precipitation, and 4) development and analysis of new satellite sensor concepts.

Two methods were developed and tested for correcting passive or active microwave surface precipitation estimates based on hydrometeors sensed aloft that may evaporate before landing. These corrections were derived using two years of data from 516 globally distributed rain gauges and three passive millimeter-wave Advanced Microwave Sounding Units (AMSU) aboard NOAA satellites (N15, N16, and N18). The first correction reduces rms differences between rain gauges and AMSU annual precipitation accumulations (mm) by a separate factor for each infrared-based surface classification, while the second correction factor uses a 3-2-1 neural network (NN) trained using both surface classification and annual average relative humidity profiles. The NN results agreed with rain gauges better than did surface classification corrections alone. The rms annual accumulation errors relative to the 516 uncorrected rain gauges using AMSU with surface classification and NN corrections were 223 and 209 mm/yr, respectively, compared to 152 mm/yr for GPCP, which incorporates rain gauge data (some of which is included in the comparison set) and data from more satellite sensors. Thus the opportunity for further improvement in such annual averages is limited.

A preliminary new retrieval algorithm was developed for the conically scanned microwave spectrometer SSMIS patterned after the algorithms developed for AMSU and ATMS [1,2]. It currently works acceptably when there is no surface snow or ice and the air is not too dry. Advantages of SSMIS relative to AMSU are that some channels view longer wavelengths or view both horizontal and vertical polarization, and the SSMIS fields of view are often smaller than those of AMSU and independent of viewing direction. Disadvantages are that the SSMIS antenna beamwidths all vary with wavelength, and the zenith angle is sufficiently large that the geometry of convective cells and the character of deep scattering become more important. The challenge is to adapt the new SSMIS retrieval algorithm to these opportunities and problems.

Current retrievals of environmental parameters from satellites are generally characterized either by variances for large ensembles of data, or by flags that warn users that the accuracy of a particular sounding or pixel may be degraded. Users would prefer accuracy estimates that vary from pixel to pixel since that variation can be significant due to the non-linear character of the physics, statistics, and retrieval in both clear air and cloudy situations. Neural networks were developed for estimating the rms accuracy profiles of individual infrared and microwave atmospheric temperature and humidity profile retrievals, thus potentially significantly improving their assimilation into numerical weather prediction models. The ability to estimate accurately the variances of individual profiles is one of the benefits of hyperspectral infrared and microwave sounding. The neural networks were trained to estimate the logarithm of variance, which was then mapped to standard deviation. Examples utilizing AIRS/AMSU/HSB soundings on the NASA Aqua satellite and those from a proposed multispectral microwave sounder show that the predicted rms errors agree with the actual rms errors for that altitude and pixel within perhaps ten percent of the dynamic range of the errors for that altitude, thus significantly improving the potential for accurately weighting such soundings when assimilating them into numerical weather prediction models [4], and therefore for improving their forecasts.

Three new satellite sensor concepts were formulated in collaboration with Lincoln Laboratory: hyperspectral microwave atmospheric sounding, microsatellite microwave imaging spectrometers, and cluster concepts for microsatellite sensors. Historically microwave atmospheric sounding of temperature and humidity profiles using the oxygen and water vapor microwave resonances has, for economic and technical reasons, employed fewer than 25 channels. Hyperspectral millimeter-wave spectrometers having over 100 channels between 50 and 200 GHz could be practical and far smaller than current systems due to miniaturization and improved receiver sensitivities. Such hyperspectral receivers offer significantly improved performance relative to prior receivers for both temperature and humidity profile retrievals because the increased number of channels captures more degrees of freedom while also reducing the effective noise levels. Further study of such polar-orbiting systems appears attractive since their anticipated contributions to numerical weather forecasts rivals that of current IR/microwave sensors of far larger size, weight, power, and cost [3].

A preliminary design study of an independent hyperspectral microwave satellite that rivals a next generation operational millimeter-wave spectrometer, ATMS on NOAA/NASA satellites, yielded an estimated sensor volume (0.004 m^3), mass (6 kg), and power (10W), compared to ATMS values of 0.17 m^3, 85 kg, and 110W, respectively. An associated spacecraft designed by Prof. David Miller of the MIT Space Systems Laboratory would add only 0.002 m^3 in a cube-sat architecture. Small clusters of such microsatellites could function as much larger systems but with much lower launch and maintenance costs since only defective satellites would need replacement. A variation of the hyperspectral configuration was also designed for use in geostationary orbits to image and track fast moving events like hurricanes and other severe storms generally obscured by cloud cover that can be penetrated by microwave sensors.

Journal Papers

1. C. Surussavadee and D. H. Staelin, "Satellite Retrievals of Arctic and Equatorial Rain and Snowfall Rates using Millimeter Wavelengths," *IEEE Trans. Geosci. Remote Sens*., vol. 47, no. 11, pp. 3697-3707, Nov. 2009.

2. C. Surussavadee and D. H. Staelin, "Global Precipitation Retrievals Using the NOAA/AMSU Millimeter-Wave Channels: Comparison with Rain Gauges," *J. Appl. Meteorol. Climatol.*, vol. 49, no. 1, pp. 124-135, Jan. 2010.

3. W. J. Blackwell, Bickmeier, L. J., Leslie, R. V., Pieper, M. L., Samra, J. E., Surussavadee, C., Upham, C. A., "Hyperspectral Microwave Atmospheric Sounding," *IEEE Trans. Geosci. Remote Sens*., Dec. 2010 (available online from ieeexplore.ieee.org).

Theses

4. Zuoyu Tao, Improved uncertainty estimates for geophysical parameter retrieval, S.M. thesis, Department of Electrical Engineering and Computer Science, June, 2010.

Study of Millimeter-Wave Satellite Precipitation Retrieval Algorithms Using MM5 Simulations

Sponsor
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This effort concluded this year with study of precipitation over Arctic sea ice, which is particularly sensitive to global warming and is evolving rapidly. The melting ice cap and increased sea cover in summer is eventually likely to change the precipitation regime. By utilizing the five or more millimeter-wave operational satellite instruments in polar orbits it should be possible to establish a climate baseline and closely monitor these summertime changes. Using the Arctic algorithm [1,2] the images in Figure 1 were obtained at ~102 minute intervals using AMSU data from the NOAA-18 operational weather satellite from 14:25 to 22:56 UTC on June 22, 2008. Neither radar data (too sparse) nor other satellites without millimeter-wave spectrometers can currently provide such images of the unique storm morphologies produced in this highly geostrophic region (where the Coriolis effect is strong).

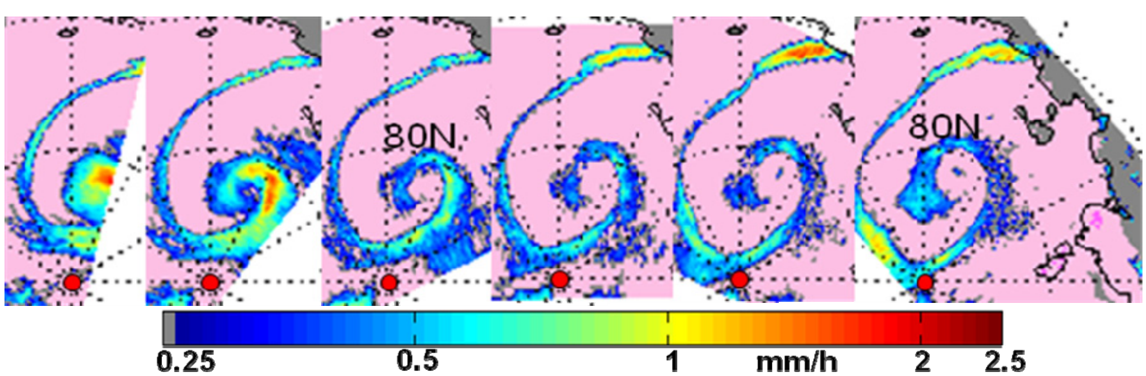

Figure 1. North Pole precipitation over ice pack (pink) viewed from AMSU on the NOAA-18 satellite at 102-minute intervals, June 22, 2008.

Journal Papers

1. C. Surussavadee and D. H. Staelin, "Satellite Retrievals of Arctic and Equatorial Rain and Snowfall Rates using Millimeter Wavelengths," *IEEE Trans. Geosci. Remote Sens*., vol. 47, no. 11, pp. 3697-3707, Nov. 2009.

2. C. Surussavadee and D. H. Staelin, "Global Precipitation Retrievals Using the NOAA/AMSU Millimeter-Wave Channels: Comparison with Rain Gauges," *J. Appl. Meteorol. Climatol.*, vol. 49, no. 1, pp. 124-135, Jan. 2010.

Spike-timing model for neural signal processing and learning

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Our preliminary model for cortical spike-based neural computation was refined so that theoretical expressions for information storage and retrieval performance of single neurons could be derived and compared to simulations as a function of neural architecture and parameters. This work involved collaboration with Carl H. Staelin of HP Laboratories, Israel.

A neuron "learned-information" metric L(bits/neuron) was defined and used to optimize rapid-learning (RL) spike-processing neural models that, during "learning readiness", can memorize for subsequent recognition multiple complex input synapse excitation patterns in seconds even if the neuron has thousands of afferent synapses. Each synapse excitation pattern for a single neuron arrives in a single wave of spikes that typically lasts less than ~20 msec; the probability that a particular synapse is excited per pattern is small. L = I[X;Y] where I is the mutual information between the learning and recall spaces, X and Y, of a neuron or system, and untrained synapses are removed at "maturity" between learning and recall testing. X and Y can be binary vectors indicating which of Z plausible patterns were taught (X) and learned (Y), where those recalled (learned) at maturity typically include some false alarms. It appears plausible that neuron learning readiness in nature could be mediated by astrocytes, which have been suspected of having an important role in learning.

It also appears likely that the RL mechanism could sequentially train multiple layers of randomly prewired neurons while avoiding the latency limits of backpropagation training. The simplest RL neural model assumes: 1) the neuron fires when H or more afferent synapses are excited within one of $D \geq 1$ alternative time intervals within a single wave of spikes (a wave might last less than 20 msec), 2) $C \geq 1$ dendrite compartments of a single neuron can sum their own synaptic excitations and fire independently, 3) typical neurons fire on average only once per R input excitation patterns (each spike wave is a "pattern"), 4) the average spike firing frequencies and delay spreads (D) are roughly the same for consecutive optimized neural layers, which allows them to function efficiently when stacked in many layers, and 5) the binary-valued synapses atrophy at "maturity" if they never contributed to any output spike during "learning readiness".

Theory and time-domain simulations independently suggest that L can approach approximately $0.6\ (DRC)^{0.9}H^{1.6} \pm 16\%$ bits/neuron and exceed 0.1 bit per mature synapse even if spikes merely indicate that the responsible excitation pattern had previously been learned. Neurons optimized for sufficiently large products HRDC can have >10,000 synapses and learn thousands of patterns. These models also suggest that: 1) the optimum average firing rate R may be determined partly by the relative degree to which organism survival depends on neural memory capacity (bits/neuron) versus information recall rates (bits/neuron/second), and 2) the optimum firing threshold H may be partly determined by the relative metabolic costs of neurons vs. synapses. It also appears likely that the RL model can enable timely training of multiple layers of top-down neural feedback paths that could facilitate pattern detection, source coding, and a network's associative memory capabilities.