Space-Time Open Architectures for Broadband Wireless Data Communications: Above the $\mathrm{Log}_2(1+\mathrm{SNR})$ Bit/Sec/Hz Barrier

Max Martone* *Member, IEEE*
WJ Communications
Palo Alto, CA 94304, USA

Abstract— **The creation of multiple channels (sharing the same time-frequency region) between a transmitter and a receiver can be achieved by sampling the wavefield space with respect to the spatial domain. The wavefield space is the signal space spanned by the channel parameters which characterize the multipath fading environment. Using this basic intuition it is possible to reliably transmit data at rates exceeding the famous Shannonian spectral efficiency of $Log_2(1 + SNR)$ bit/sec/Hz where SNR is the signal-to-noise ratio over the bandwidth occupied by the signal. This exciting possibility has generated significant interest in the communications community. However, it is not clear at this point how a realistic and cost-effective radio could take advantage of such an enhancement. WJ Communications has invested significantly in the reasearch of this subject and sponsored the study of a new transmission scheme, STREAM$_{TM}$, [Spatial Transmission with Radio Enhanced Adaptive Modulation] able to achieve very high speed bandwidth-efficient wireless data communications in arbitrary environment: outdoor/indoor, mobile/fixed, line-of-sight/obstructed. We describe here the general ideas of the technology and show the results of the first hardware prototype which has no counterpart currently in industry in terms of scaleability, cost, performance.**

I. BACKGROUND

High speed data services are today a requirement of the wireless communication industry. Unfortunately, the achievement of high data rates in the wireless environment is still a technical challenge. In presence of additive white Gaussian noise (AWGN)[1] a well known limit to the maximum achievable data rate is the Shannon-Nyquist bound: having an available channel bandwidth W and signal to noise ratio over this bandwidth equal to SNR, it is impossible to transmit reliably data at a rate higher than $C = Wlog_2(1 + SNR)$ (in bits per second). In other words the maximum spectral efficiency is bounded at any signal to noise ratio by $Log_2(1+SNR)$ bit per second per Hertz. The fundamental point in this famous formula is that the number of dimensions per unit-time that can be accomodated by an approximately W-bandlimited channel is bounded by $2W$. This result is due to Landau and Pollak [1]. Many researchers observed that multiple transmit/receive antennas have a substantial benefit on the achievable data rate in multipath fading environments [4], and actually that the transmission with a U-sensor antenna array and reception with a K-sensor antenna array is capable of achieving rates that increase linearly with $min(U, K)$ [2]. In other words, one can expect an increase in capacity directly proportional to the number of sensors at the antenna array without any penalty in power and bandwidth. The subject has generated significant interest in the communication research community in recent years. In the United States there are several independent industry efforts that have attacked a similar problem. One of them finds its roots at Lucent where a system called BLAST (Bell-Labs Space-Time Architecture) was developed for a non-frequency selective, static (typically indoor) environment with extremely narrowband throughput. Despite the undeniable value of that first study we clearly see the restricted applicability of the investigation.

The study sponsored by WJ Communications has solved a more general problem: cost-effective methods to demodulate broadband data rate signals transmitted from different positions in the wavefield, afflicted by arbitrarily time-varying fading characteristics, with arbitrary time dispersion. The result of the study is a method defined STREAM$_{TM}$ (Spatial Transmission with Radio Enhanced Adaptive Modulation).

II. SUMMARY OF THE TECHNIQUE

The wavefield space is the space spanned by the channel parameters that characterize the multipath fading environment. At the transmitter symbols are modulated and simultaneously transmitted using signals that occupy the same frequency portion of the spectrum, but are distinguishable because different is their position in the wavefield space. The shape of the wavefield space depends on the particular propagation environment. The optimum demodulator estimates the wavefield space parameters and

---

* Email: max.martone@wj.com.

[1] In a sense the AWGN channel model is the simplest channel model. In fact in reality many other sources of distorsion place additional limitation to the maximum achievable data rate. As a consequence the AWGN channel capacity has always been considered an upper bound to the capacity of any other channel model.

0-7803-6454-6/00/$10.00 (C) 2000

performs optimum separation of the different signals to obtain the multiple streams. Given a perfect estimate of the wavefield space parameters, the Maximum Likelihood principle is the optimum strategy for detection. When the wavefield space parameters are *a-priori* unknown, the Maximum Likelihood detector can not be implemented. A typical approach is the Generalized Likelihood Detector (GLD) [18] which uses the Generalized Likelihood statistic (GLS) to detect the signals. The Generalized Likelihood statistic, derived for time-varying wavefield spaces, involves finding the orthogonal projection of the received signal onto the signal subspace: the transmitted signal (corresponding to one of the transmitted sequences of symbols) is in fact known to lie in a subspace but its exact location is not known, because unknown are the wavefield space parameters. Detectors in this class are also called in signal processing *matched subspace detectors* [16] because their statistic is "matched" to the *a-priori* known signal subspace $\mathcal{S}$. The (perfectly matched) orthogonal projection of the received signal onto the signal subspace $\mathcal{S}$ is difficult (if not impossible) to compute. STREAM$_{TM}$ employs subspaces, say $\mathcal{V}$, that approximate the original signal subspace $\mathcal{S}$ in some sense, and whose orthogonal projections are more easily computed. These reduced-size signal subspaces $\mathcal{V}$ are obtained by means of a decomposition of the fading channel time variations using orthonormal wavelet bases [9]. Consider $\tilde{f}(t,\tau)$, as the wavefield space response to an impulse at time t. A multiresolution decomposition can be applied to $\tilde{f}(t,\tau)$ at any τ with respect to t as

$$\begin{aligned}\tilde{f}(t,\tau) &= \sum_{m}\zeta(m,\tau)2^{-P/2}\phi(2^{-P}t-m)\\ &\quad+\sum_{l=-\infty}^{P}\sum_{m}\xi(l,m,\tau)2^{-l/2}\psi(2^{-l}t-m), \quad (1)\end{aligned}$$

where $\xi(l,m,\tau)$ are wavelet coefficients, $\zeta(m,\tau)$ are scaling coefficients, $\psi(t)$ is a prototype bandpass wavelet function and $\phi(t)$ is a lowpass scaling function [7], [8]. Observe that l indexes the *scale*, or *resolution* (the smaller l the higher the resolution), while m indexes the *spatial* location of analysis. If the mother wavelet is centered at time 0 and frequency f_c, $\xi(l,m,\tau)$ measures the content of $\tilde{f}(t,\tau)$ around time $2^l m$ and frequency $2^{-l}f_c$, while $\zeta(m,\tau)$ represents the local mean around time $2^P m$.

The well-known merits of this decomposition are justified by an outstanding localization capability in the time-frequency plane (see [9]). Using expansions for a generic signal by means of orthonormal functions that are well-localized in the time-frequency plane implies that only a few coefficients of the expansion can be adopted to represent with extreme accuracy the original signal. Basically the method uses an efficient representation of the fading statistics in the maximum likelihood formulation of the detection problem.

In fact, the set of linear vector spaces defined by such decomposition provides also a nested sequence of subspaces that, at increasing level of detail, are "efficient" representations of the original signal subspace $\mathcal{S}$. Part of the STREAM$_{TM}$ method is a method to "focus" these (subspace) representations to the original signal subspace using the concept of Kolmogorov $n$width for signal classes. The system model described in this subsection is described in more detail in [12], [13], [14]. Consider a K-element antenna receiving signals from a U-antenna transmitter represented as

$$y_k(n) = \mathbf{a}(n)^T\mathbf{h}_k(n) + \eta_k(n), \quad (2)$$

with $\mathbf{a}(n) = [a_1(n), ...a_1(n-D), ..., a_U(n), ...a_U(n-D)]^T$ as the vector of transmitted symbols, and

$$\mathbf{h}_k(n) = [g_{k,1}(n,0), ..., g_{k,U}(n,D)]^T .$$

as the channel vector at time-step n, $\eta_k(n), y_k(n)$ additive Gaussian noise and received sample at the kth antenna. According to the Maximum Likelihood (ML) principle the optimal detection metric is

$$\begin{aligned}L_N &= -\sum_{n=0}^{NR-1}\sum_{k=1}^{K}|y_k(n)-\boldsymbol{\alpha}(n)^T\mathbf{h}_k(n)|^2\\ &= -\sum_{n=0}^{NR-1}\sum_{k=1}^{K}|y_k(n)-s_k(n)|^2\\ &= -||\mathbf{y}-\mathbf{s}||^2. \quad (3)\end{aligned}$$

Since the wavefield space is assumed unknown, the optimal metric can not be eactly computed and the application of the Generalized Likelihood (GL) argument results in the statistic

$$\mathcal{L}_N = ||\mathbf{P}_{\mathcal{S}}[y]||^2, \quad (4)$$

where $\mathbf{P}_{\mathcal{S}}[y]$ is the orthogonal projection of $\mathbf{y}$ onto the signal subspace, denoted $\mathcal{S}$. If no specific structure of $\mathbf{h}_k(n)$, for $n = 0, 1, ..., NR-1$ and $k = 1, ..., K$, is assumed it may be impossible to find $\mathbf{h}^{\boldsymbol{\alpha}}_{[ML]}$, the conditional maximum likelihood estimate of $\mathbf{h}_k(n)$. There may be infinitely many orthogonal projectors onto the non uniquely defined signal subspace for each transmitted sequence (this problem is a rather fundamental problem in estimation theory whose continuous time counterpart is pointed out in [18] p. 456). The GL statistic involves finding the orthogonal projection of the received samples y_n onto the signal subspace $\mathcal{S}$: the signal is known to lie in the subspace $\mathcal{S}$ but its exact location is unknown because $\mathbf{h}$ is unknown. The detectors described by (4) are *matched subspace detectors* [16], because they are "matched" to the signal subspace $\mathcal{S}$. Moreover, since they form their statistic according to the energy of the orthogonal projection of the received signal onto the signal subspace, they can be also interpreted as *generalized energy detectors.*

STREAM$_{TM}$ relates to the discovery that alternative subspaces $\mathcal{V}$ with orthogonal projections that are computed more easily than $\mathbf{P}_{\mathcal{S}}[y]$, exist.

This results in generalized energy detectors that are not perfectly matched to $\mathcal{S}$ but still perform satisfactorily in the sense that

$$||\mathbf{P}_{\mathcal{S}}[y]||^2 \simeq ||\mathbf{P}_{\mathcal{V}}[y]||^2.$$

III. DESCRIPTION OF HARDWARE ARCHITECTURES

Wideband Radios use a single Radio Frequency path to access the entire allocated band, performing traffic channelization via digital signal processing. Traditional radios perform traffic channelization in hardware and typically require additional hardware combining network for multi-channel systems. The flexibility increase inherent to wideband stems from the fact that the channelization process can be done in software or reconfigurable logic which can not only be upgraded but could be dynamically changed on a connection by connection basis [17].

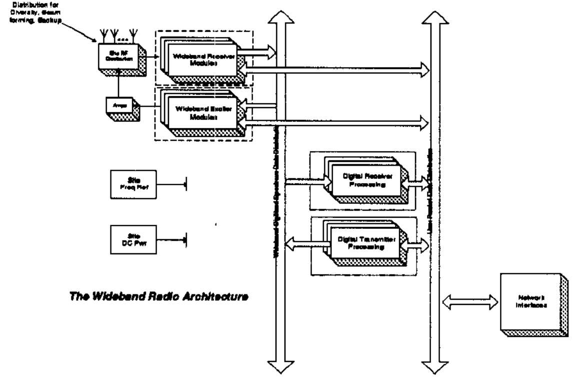

Fig. 1. The Hardware architecture of the Transceiver developed by Watkins-Johnson.

Fig. 1 shows a Wideband architecture for a transceiver. A plurality of receiving antennas are connected to the site RF distribution which is a network of RF signal distribution circuits. The Power Amplifiers are necessary to amplify the transmit signal to reach the remote receiver at adequate distance. The Wideband Receiver Modules (one per antenna) are in charge of filtering, amplifying, downconverting and digitizing the RF spectrum of interest. The digital samples at the output of the ADC from each of the Wideband Receiver Modules are routed appropriately time-multiplexed to the Wideband Digitized Spectrum Data Distribution. Digital Receiver Processing modules perform traffic channelization, demodulation and data extraction. In the transmit path the digital transmitter, the Wideband Exciter perform the reverse operations.

The Wideband Receiver and Exciter RF Modules functional diagrams are illustrated in Fig. 2.

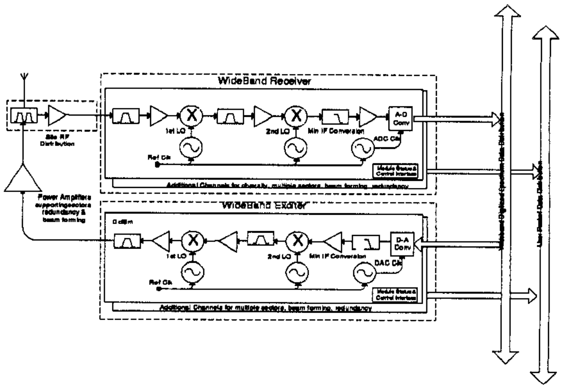

Fig. 2. The RF section of the transceiver with Analog to Digital and Digital to Analog conversions.

The wideband receiver is designed to be driven from a site RF distribution network and minimizes this interface requiring a single, low gain RF feed per antenna element. High dynamic range amplifiers and mixers are utilized to obtain a large instantaneous dynamic range preserving signal fidelity. The signal as collected by the antenna is filtered, amplified, further filtered and amplified. It is then mixed by a first Local Oscillator and filtered, amplified and mixed down to intermediate frequency by a second Local Oscillator. A filter removes unwanted high frequency components and the resulting signal is further amplified before being injected to the analog to digital converter. The clock to the to the analog to digital converter is generated by a frequency source locked to the site frequency reference. The samples at the output of the Analog to Digital Converter are routed to the Wideband Data Distribution Bus. This Bus is a high speed Time Division Multiplexed resource that connects any RF module to any Digital receiver module in a non-blocking fashion. All frequency and clock conversion oscillators are locked to the external site frequency reference ensuring coherent operation. The Wideband Exciter RF Module is also illustrated in Fig. 2. The samples from the Wideband Data Distribution Bus are routed to the the Digital to Analog Converter. The analog signal then is filtered, amplified and mixed using the second Local Oscillator frequency. The RF signal is further filtered, amplified and upconverted using the first Local Oscillator frequency. After proper amplification and filtering the signal goes to a multicarrier power amplifier that is responsible for providing enough RF power to the signal to reach the remote receiver after antenna radiation.

The traffic channelization (that is baseband conversion) is performed using digital quadrature downconversion implemented by means of specialized high-speed ASIC. The samples from the Wideband Digitized Data Distribution are downconverted to baseband by means of a quadrature mizer where the mixing frequency is agenerated by a NCO (Numerically Controlled Oscillator). An NCO is a digital implementation of what is known in the analog domain as Voltage Controlled Oscillator. The two branches (In-Phase and In-Quadrature) samples are filtered to remove high frequency components of the mixing process. Each of the digital downconverters is connected to pulse shaping filters that are matched to the tranmsitted pulse shapes and the output of these filters are sampled at a rate that is an integer multiple of the symbol rate. These samples are known to contitute a sufficient statistic for the detector previously described. The synchronizer is responsible for optimizing the sampling instants at the output of the sahping filter. Wavefield estimation is performed iteratively using the Generalized Likelihood method described and the gradient update scheme. The processing functions following the demodulation are related to the channel coding section of the communication system. A deinterleaver with channel decoder function follows the demodulator. Data extraxtion refers to the organization of the information bitstream in a way that is compatible with the partricular application of the communication system. The data is first properly organized in a bitstream from the user packet data distribution bus by means of the data extreaction function. Then it is properly encoded and interleaved. The modulator basically organizes the high-speed single bitstream in multiple lower speed bitstreams. These bitstreams are modulated according to the particular digital modulation format of interest (for example M-QAM or M-PSK) and routed to the pulse shaping filters. The device that follows is a digital upconverter that basically translates to a first intermediate frequency the baseband signal at the output of the pulse shaping filters. The digital upconverter is constituted by filters, mixers (multiplers), a Numerically Controlled Oscillator and an adder. The digital samples at the output of the digital upconverter are routed by means of the Wideband Digitized Spectrum Data Distribution Bus to the respective Wideband Exciter RF module where they are converted to analog signals and upconverted to RF. Each module is controlled by a microcontroller, able also to provide interfaces with the data distribution resources (Wideband Digitized Spectrum Data Distribution and User Data Distribution. Multiple modules can be replicated to meet traffic capacity and/or multiple antenna requirements.

IV. RESULTS OF HARDWARE EXPERIMENTS

WJ Communications has developed a hardware prototype which enabled STREAM$_{TM}$ with up to 12 transmit antennas and 15 receive antennas. The bandwidth of the radio is selectable up to 5 MHz. The functional hardware architecture described in the previous Section is mapped to the wideband base-station of [17]. After the incident composite frequency-multiplexed signal has been received at RF by the antenna system the wideband receive section translates frequency of the received RF signal to an analog baseband frequency. The analog baseband signal is then digitized into 12-bit samples by an analog to digital converter, and the resultant data stream is provided to a time-division multiplexed (TDM) local receive bus operative at a rate of 30.72 Msps (see Fig. 3). The local receive bus is implemented as a standard VXI Local Bus as specified in VXI Specification, IEEE Standard 1155.

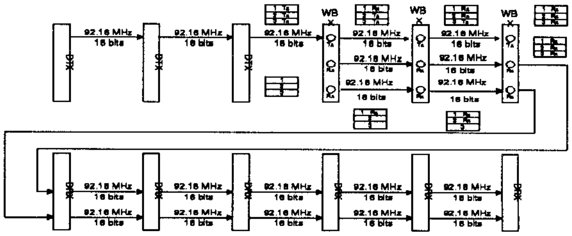

Fig. 3. The Wideband Data distribution architecture. The bus used is a VXI bus, as specified in VXI Specification, IEEE Standard 1155.

We present results for the cellular band and for the 3.5 GHz licensed band.

Fig. 4 show result for 12 transmit antennas and 15 receive antennas and 30 KHz bandwidth in the cellular band (IS-136 band).

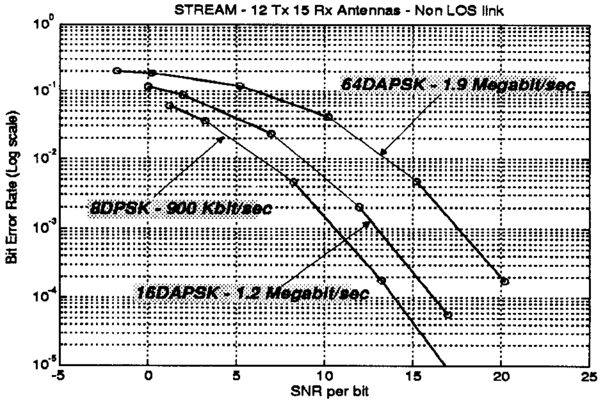

Fig. 4. Bit Error Rate results averaged over 100 different locations for obstructed (non Line of Sight) environment with 12 transmit antennas, diversity gain equal to 4/5.

A. A wireless broadband scenario

In Fig. 5 we show hardware results of a typical fixed wireless broadband access scenario. The delay spread is about 10 μsec and the bandwidth used by the radio is 4 MHz. We achieve a data rate in the vicinity of 72 Mbit/sec. It is important to emphasize the robustness of the digital radio to heavily dispersed channels without the use of a multicarrier methodology.

The details of the methodology to cope with large amount of ISI are proprietary.

The Peak to Average Ratio remains within 6dB which makes the technique significantly more advantageous than OFDM from the radio cost point of view.

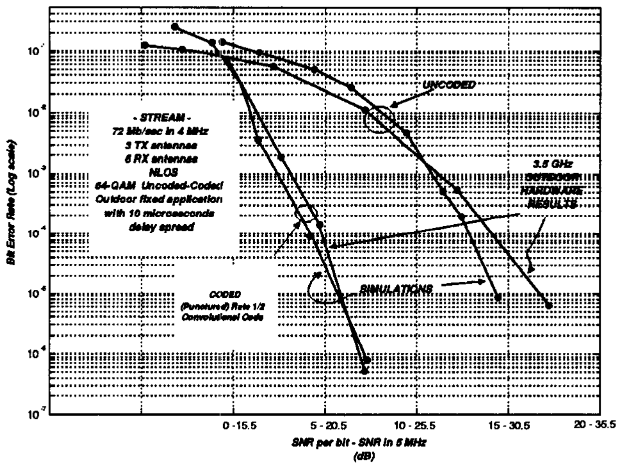

Fig. 5. Bit Error Rate results averaged over 10 different locations for outdoor obstructed (non Line of Sight) environment with 3 transmit antennas. The bit rate is about 72 Mbit/sec.

V. CONCLUSIONS

We have described the architectural implications of a new technnology, STREAM$_{TM}$, able to achieve very high speed bandwidth-efficient wireless data communications exploiting the wavefield space with arbitrary environemnt: outdoor/indoor, mobile/fixed, line-of-sight/obstructed. The modem can detect high speed data in rapidly time varying fading multipath making use of a model that more accuractely characterizes the time-variant nature of the detection problem. This technonology has no counterpart currently in industry, in fact the described hardware architecture outperforms most known technologies in terms of scaleability, cost, performance.

REFERENCES

[1] H. J. Landau and H. O. Pollak "Prolate spheroidal wave functions, Fourier analysis and uncertainty-III: the dimensions of the space of essentially time and band-limited signals", *Bell Systems Tech. J.*, vol. 41, pp 1295-1336, July 1962).

[2] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," *Bell Labs Tech. J.*, vol. 1, no. 2, pp. 41-59, 1996.

[3] V. Tarrokh, N. Seshadri and A. R. Calderbank, "Space-Time Codes for High Data Rate Wireless Channels Communication: Performance Criterion and Code Construction", *IEEE Transactions on Information Theory* , vol. 44, n. 2, March 1998.

[4] J. Winters, "On the capacity of radio communication systems with diversity in a Rayleigh fading environemt," *IEEE J. Select. Areas Commun.*, vol. SAC-5, pp. 871-878, June 1987.

[5] G. G. Rayleigh and J. M. Cioffi, "Spatio-temporal coding for wireless communication," *IEEE Trans. Commun.*, vol. 46, pp. 357-366, Mar. 1998.

[6] P.A. Bello, "Characterization of randomly time variant linear channels", *IEEE Trans. Comm. Syst. Tech.*, vol. 11, pp. 360-393, December 1963.

[7] I. Daubechies, *"Ten lectures in Wavelets"*, SIAM, New York, 1992.

[8] I. Daubechies. "Orthogonal bases of compactly supported wavelets" *Commun. Pure Appl. Math.* , vol. 41, pp. 909-996, 1988.

[9] D. L. Donoho, "Unconditional bases are optimal bases for data compression and for statistical estimation" *App. Comp. Harmonic Anal.*, pp. 100-115, Dec. 1993.

[10] G. D. Forney. "Maximum Likelihood Sequence Estimation of Digital Sequences in the Presence of Intersymbol Interference". *IEEE Trans. Inform. Theory*, vol. IT-18, pp. 363-378, May 1972.

[11] J. Liang and T. W. Parks, "Kolmogorov n-widths and wavelet representation for signal classes" *IEEE Trans. Sig. Proc.*, vol.44, pp. 1693-1703, Jul. 1996.

[12] M. Martone, "An adaptive algorithm for adaptive antenna array low-rank processing in cellular TDMA base-stations", *IEEE Trans. Commun.*, vol. 46, pp. 627-643, May 1998.

[13] M. Martone, "On MMSE Real-Time Antenna Array Processing Using Fourth-Order Statistics in the US Cellular TDMA System", *IEEE Journal Sel. Areas in Comm.*, Vol. 16, N. 8, pp. 1396-1410, Oct. 98.

[14] M. Martone, "Cumulant-based adaptive multi-channel filtering for wireless communication systems with multipath RF propagation using antenna arrays" *IEEE Trans. Veh. Tech.*, Vol. 47, no. 2, pp. 377-391 May 98.

[15] J. G. Proakis. *"Digital communications"*. McGraw-Hill, Third Edition, 1995.

[16] L. L. Scharf. *"Statistical Signal Processing"*, Addison Wesley, 1991.

[17] US Patent No. 5678268, *"Wideband Base Station Architecture for Digital Communications System"*, Filed Jul. 19 1995, Issued Jun. 16 1998.

[18] L. Van Trees. *"Detection, Estimation, and Modulation Theory"* Part I, John Wiley 1968.

[19] P.P. Vaidyanathan, *"Multirate Systems and Filter Banks"*, Prentice Hall, 1993.