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Multiple transmit multiple receive (MTMR) capacity survey in Manhattan

J. Ling, D. Chizhik, P. Wolniansky, R. Valenzuela, N. Costa and K. Huber

A multiple transmit multiple receive (MTMR) capacity survey has been performed in Manhattan, New York for mobile and pedestrian wireless services, using 16 transmitters and 16 receivers. Shannon capcities close to the Rayleigh i.i.d. have been measured for 2 Tx 2 Rx, 4 Tx 4 Rx, 16 Tx 16 Rx systems.

Introduction: Information theory research has shown that multiple transmit multiple receive (MTMR) arrays can achieve enormous capacity gains over single-antenna systems by exploiting multipaths in the rich scattering wireless channel [1, 2]. Practical signalling schemes have been proposed which achieve a large fraction of the Shannon capacity, and one such scheme is the Bell Labs Layered Space Time (BLAST) scheme [1, 3]. Previous measurements have focused on suburban areas [4, 5]. In this Letter we present the results of a survey of narrowband MTMR channel measurements for an area of Manhattan. The base array was mounted 100 m above street level, and the terminal array was mounted on a van at a height of 1.5 m. We evaluate the Shannon capacity of the MTMR channel for a plausible configuration of two and four antennas for handheld, and sixteen antennas for laptop terminal devices. To observe the relative merit of a given MTMR channel, the measured capacity is compared to the capacity given a Rayleigh i.i.d. channel.

Experiment design: A narrowband radio was built to measure the complex channel coefficients between a 16 element transmit array and a 16 element receive array. The transmitter sends 16 tones, one on each antenna. The receiver consists of 16 identical radio chains, and an A/D card, which can simultaneously sample all receivers. To identify the tones at the receiver, the fast Fourier transform (FFT) is used. At 20 miles per hour matrices are taken every 1/8th of a wavelength, which is short enough to consider the channel static. Noise measurements are made continuously at a frequency outside the transmit band. The carrier frequency was 2.11 GHz, and the transmit power was 20 dBm per element.

The base array is a horizontal linear array of eight pairs of antennas. Each pair consists of a vertical and horizontally polarised element. The length of the entire array is 3 m, twenty wavelengths at 2 GHz, corresponding to the spacing of diversity antennas at the cellular basestations. Each element is a slot antenna. The terminal array is square, with one half wavelength between elements and oriented in the vertical plane with alternating polarisations.

MTMR capacity: Assume that the channel is unknown to the transmitter, and the total transmit power P_t is equally allocated to all antennas. Let the number of transmit antennas be n_t and number of receive antennas be n_r. The capacity of the MTMR system has been derived in [1] as

$$C(\rho) = \log_2 \det\left[\mathbf{I}_{n_r} + \left(\frac{\rho}{n_t}\right)\mathbf{HH}^*\right] \quad \text{bit/s/Hz} \qquad (1)$$

We define the average SNR, also called the system SNR, as $\rho = P_r/N_o$ where P_r is the average received power. **H** is the normalised $n \times n$ channel matrix, the entries of which have unit power, N_o is the power of AWGN, **I** is the identity matrix of dimension n_r, and $\mathbf{H}^*$ means take the complex conjugate transpose. ρ is set to 10 dB, regardless of actual P_r. Measured **H**s are entered into eqn. 1. The measured SNR is monitored to ensure that the apparent capacity increase from thermal noise is less than 10%.

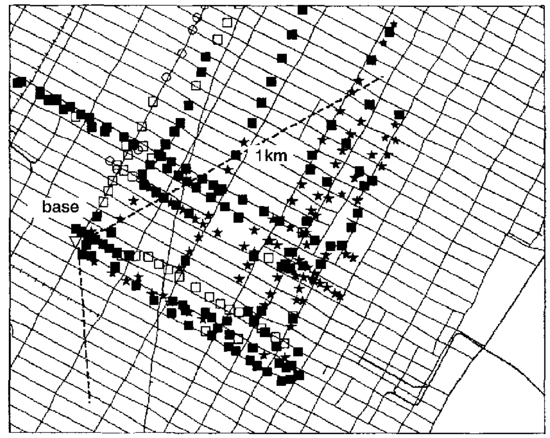

Fig. 1 *Capacity plot of midtown Manhattan*

○ 15 bit/s/Hz or less
□ 15 to 25 bit/s/Hz
■ 25 to 35 bit/s/Hz
★ 35 to 44 bit/s/Hz

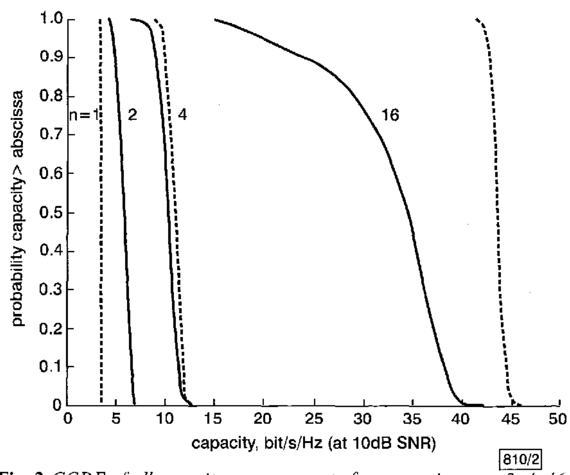

Fig. 2 *CCDF of all capacity measurements for array sizes n = 2, 4, 16*

——— measured
– – – – Rayleigh i.i.d.

Results and conclusion: Fig. 1 shows a capacity plot of midtown Manhattan. The dashed lines show the –6 dB antenna beamwidth and the various capacities are denoted by different symbols. Fig. 2 is a complementary CDF of all locations within the beamwidth of the base antenna pattern. The Figure shows Shannon capacities close to the Rayleigh i.i.d. channel. At median coverage, for $n_t = n_r = 2$ the measured capacity is 99% of Rayleigh i.i.d., for $n_t = n_r = 4$ measured capacity is 95% of Rayleigh i.i.d., and for $n_t = n_r = 16$, measured capacity is 77% of Rayleigh i.i.d.

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Simultaneous optimisation of window and frame size for maximum throughput IrDA links

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A new method for simultaneous optimisation of both window and frame size link layer parameters for maximum IrLAP throughput is presented. The significance of the F-timer value on throughput performance is explored. A protocol improvement that utilises special supervisory frames (S-frames) to pass transmission control is proposed. This results in maximum throughput performance when both optimal window and frame size values are implemented.

Introduction: Millions of devices, such as laptops, printers, digital cameras and mobile phones, are shipped every year equipped with infrared wireless ports [1]. The devices follow standards defined by the Infrared Data Association (IrDA) for their information transfer needs. IrDA addresses low cost, point to point, indoor links. The links are half duplex of data rates ranging from 115.2 kbit/s using standard serial hardware to 16 Mbit/s with high-speed hardware extension. IrDA hardware is driven by IrLAP [2], the IrDA data link layer. Analytical models for IrLAP throughput are discussed in [3] and an IrLAP performance analysis has been presented in [4]. Optimum IrLAP performance for maximum throughput for high BER can be achieved by adjusting link layer parameters, such as window and frame size. Use of optimum window size values for fixed frame size or optimum frame size values for fixed window size and the resulting throughput improvement are presented in [5]. This Letter studies the optimisation of IrLAP throughput performance by simultaneous adjustment of window and frame size parameters. Simple equations for simultaneously optimal window and frame size values for maximum throughput are derived by taking the first derivative of the throughput equation. Results indicate that the simultaneous adjustment reaches the maximum throughput performance for any BER and is therefore better than the single adjustment of either window or frame size. Current analysis reveals that the time detriment due to t_{Fout} timer expiration significantly reduces throughput performance when window and frame size are simultaneously adjusted. A protocol improvement that reduces t_{Fout} timer delays is proposed. For this improvement, the analytical model based on the concept of 'window transmission time' [3] is modified and a new simple formula for IrLAP throughput is reached. Throughput performance is greatly increased by employing the proposed protocol improvement and simultaneous optimal window and frame size values.

Optimum throughput analysis: Table 1 lists the symbols used for IrLAP analysis. The symbols for t_S, t_I, t_{ack}, p and D_b are defined by:

$$t_S = \frac{l'}{C} \qquad t_I = \frac{l+l'}{C} \qquad t_{ack} = 2t_{ta} + t_S$$
$$p = 1-(1-p_b)^{l+l'} \qquad D_b = lD_f \tag{1}$$

Throughput D_b is given by [5]:

$$D_b = l\frac{1-p}{p}\frac{(1-(1-p)^N)}{Nt_I + p(t_{Fout}+t_S)+t_{ack}} \tag{2}$$

Optimum values for window size N for fixed l and optimum values for frame size l for fixed N are given by [5]:

$$N_{opt} = \sqrt{\frac{2t_{ack}C}{l^2 p_b}} \qquad l_{opt} = \sqrt{\frac{2(Nl' + t_{ack}C)}{N^2 p_b}} \tag{3}$$

Using eqn. 2, deriving $\partial D_b/\partial N$ and $\partial D_b/\partial l$ and solving for $\partial D_b/\partial N = \partial D_b/\partial l = 0$, we derive the simultaneous optimal N and l values for maximum throughput. To a good approximation, they are given by

$$l_{opt} \simeq \sqrt{\frac{l'}{p_b}} \qquad N_{opt} \simeq \sqrt{\frac{2t_{ack}C}{l'}} \tag{4}$$

Table 1: Parameters used in modelling IrLAP throughput

Symbol	Parameter description	Unit
C	Link data baud rate	bit/s
p_b	Link bit error rate	–
p	Frame error probability	–
l	I-frame message data length	bit
l'	S-frame length/I-frame overhead	bit
t_I	Transmission time of an I-frame	s
t_S	Transmission time of an S-frame	s
t_{ta}	Minimum turnaround time	s
t_{ack}	Acknowledgment time	s
t_{Fout}	F-timer time-out period	s
D_f	Frame throughput	frames/s
D_b	Data throughput	bit/s

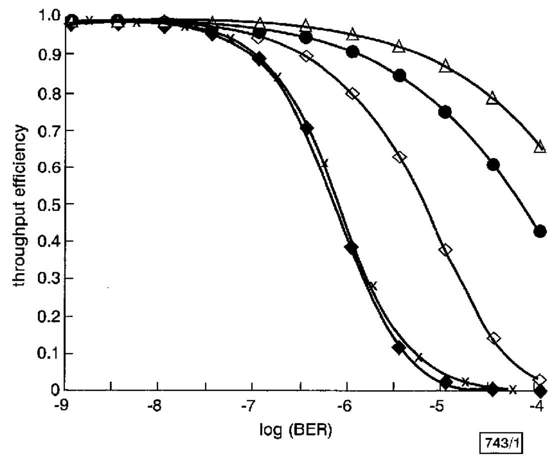

Fig. 1 *Throughput against BER for 16 Mbit/s link, t_{Fout} = 500 ms*

◆ N = 127, l = 16 kbits, t_{ta} = 0.1 ms, non optimum
◇ optimum N and l, t_{ta} = 0.1 ms
× N = 127, l = 16 kbits, t_{ta} = 0.1 ms, P-bit in RR, non optimum
● optimum N and l, t_{ta} = 0.1 ms, P-bit in RR
△ optimum N and l, t_{ta} = 0.01 ms, P-bit in RR

Results and protocol improvement: Fig. 1 compares throughput efficiency against BER for 16 Mbit/s links employing N = 127 frames and l = 16 kbits with links employing optimal window and frame size values simultaneously. For links with N = 127 frames and l = 16 kbits, throughput degrades with increase of BER owing to the large number of out of sequence frame transmissions [5], i.e. frames following an error frame in a windows transmission. By employing optimal window and frame size values simultaneously, the probability of out of sequence frame transmissions is reduced and a significant throughput increase is observed. The remaining factor that reduces throughput is the time detriment due to t_{Fout} timer expiration as shown in Fig. 2. The situation is explained as follows.

The primary station reverses link direction by setting the P-bit in the last I-frame it transmits. As BER increases, frame error probability is increased and many I-frames with P-bit set are lost. As a considerable amount of delay time (500 ms) is used for every lost P-bit, throughput efficiency degrades seriously. A protocol