Rectenna Session: Micro Aspects

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There are two micro aspects of the rectenna design which will be addressed in this presentation: evaluation of the degradation in net rectenna RF to DC conversion efficiency due to power density variations across the rectenna (power combining analysis) and design of Yagi-Uda receiving elements to reduce rectenna cost by decreasing the number of conversion circuits (directional receiving elements). The first of these micro aspects involves resolving a fundamental question of efficiency potential with a rectenna, while the second involves a design modification with a large potential cost saving. These tasks were investigated under contract with JSC during 1978.

Power Combining Analysis

In the rectenna, numerous rectifier circuits share a common DC load to achieve useful power levels. The rectifier outputs can be combined in series and/or parallel to enhance the voltage and/or current level respectively, with previous rectennas designed with first stage parallel combining followed by series combining.

A fundamental question in this receiving, rectification and power combining process is caused by the power taper of the incident microwave beam. The incident power density can vary by 10 dB over the rectenna area since a high percentage of the transmitted microwave power needs to be collected and the power beam sidelobe level must be kept reasonably low. Since the output (DC terminal) characteristics of the rectifier are power dependent, rectifiers at different power levels that share a common DC load cannot be operated at optimum conditions. With individual rectifiers near 90% maximum efficiency, the resultant efficiency degradation could be significant. In this work the efficiency degradation that results when an array of microwave power rectifiers shares a common DC load was evaluated for the first time.

In analyzing the degradation, we assume that the output load line or volt-ampere (V-I) characteristics of each of the rectifying circuits to be combined are known. This V-I characteristic can be determined by either a circuit analysis of the rectenna element, by a computer simulation or by direct measurement of the output voltage and current for several load resistances. It is assumed that the V-I characteristics are a function of some parameter θ of the rectenna element (in our case incident RF power). Given the V-I characteristics, it is possible to determine the operating point for maximum power output.

In Fig. 1 we show the V-I characteristics of two dissimilar rectenna elements as well as the points at which each of them deliver maximum power if operating independently. The same figure shows that if the elements are operated in parallel (common output voltage) or in series (common output current), they will not operate at their optimum power output and their combined power output will be less than if operated independently. We have developed expressions for the power combining inefficiency (reduction in output power compared to collected power assuming each rectifier operated in its own optimum DC load) for both series and parallel combining.(1,2)

In order to evaluate the power combining inefficiency an accurate output equivalent circuit model of the conversion circuitry is needed. This was obtained using two independent approaches. First, an approximate closed form circuit model of the rectifier was developed assuming an ideal diode and lossless circuit elements. The output load line was then obtained analytically. Second, a more precise computer simulation model was used, and the output equivalent circuit was obtained by varying the DC load resistance and plotting the resultant output load line.

We have shown that assuming an ideal diode, the circuit indicated in Figure 2A has yielded 100% conversion efficiency if $L_3 - C_3$, $L_5 - C_5$ etc. form odd harmonic parallel resonant circuits, C_1 series resonates the resultant inductive impedance at the fundamental frequency and $R_L = (\pi^2/8)\ R_S$.(1,2) Figure 2B indicates the more exact computer simulation model, a reasonable representation of the actual circuitry used in experimental rectennas. The models and the resulting load lines will be discussed further in the presentation.

When using these models and various assumed power density variations, we find that parallel combining is marginally better than series combining and that the closed form analytical model slightly underestimates the power combining inefficiency compared to the computer simulation results. Assuming a uniform power density distribution, the power combining inefficiency is 1.0% when the ratio of maximum to minimum power density is 2.0 to 1.0, reducing to 0.3% if the ratio is 1.4 to 1.0. This has an important effect on the design of the rectenna DC power combining network, favoring ring combining rather than row combining particularly near the rectenna edge.

Directional Receiving Elements

A principal advantage of the rectenna concept for the receiver in free-space microwave power transmission systems is that the effective receiver pattern is sufficiently non-directional (i.e. beamwidth sufficiently large) that receiver steering is not required. However in evaluating the requirements for a solar power satellite (SPS) with a small orbit eccentricity in a near zero inclination geostationary orbit, it became apparent that the half wave dipole separated by $\approx 0.2\ \lambda$ from a conducting ground plane has a more non-directional pattern than needed. That is the beamwidth of the receiver pattern at which 1% of the incident power is not received (0.04 dB beamwidth)* is much larger than the off normal incidence due to orbit considerations. Since the rectenna cost is projected to be $\sim$ 25% of the total system cost, consideration of more directional receiving elements is clearly desirable.

In most applications fewer RF to DC conversion circuits (favoring directional elements) and power beam pointing requirements (favoring non-directional elements) are expected to dominate the directionality issue. An additional factor with the present GaAs Schottky diode rectifiers and present SPS design values is that higher RF to DC conversion efficiency is possible at higher power levels (power density limited by nonlinear interactions in ionosphere and possibly biological factors), thus favoring somewhat more directional elements. An additional disadvantage to directional receiving elements are more stringent requirements for a stable rectenna structure and precise element tolerances.

In considering alternate receiving elements at the modest gain enhancement considered desirable, we focused on the Yagi-Uda element because of

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* Since efficient power transmission is paramount in the SPS application, a 1% beamwidth is more applicable than either the 3 dB or 1 dB beamwidth used in many microwave applications.

its simplicity. Including proximity effects in an actual array configuration was beyond the scope of our program. Instead we utilized antenna performance of isolated Yagi-Uda arrays in arriving at the expected electrical performance depicted in Table 1.(1,3)

Based upon this electrical performance we designed three and six element Yagi-Uda arrays, with and without ground plane reflector, in both conventional baseline construction and in printed circuit form. Design of three element Yagi-Uda elements without ground planes are depicted in Fig. 3. These designs will be discussed further in the presentation.

The resultant costs obtained are in our investigation presented in Table 2, the trend toward lower cost with increased rectenna element gain being apparent. As expected, the cost reduction per unit rectenna area varies between the ratio of element densities (dependent upon effective area of each receiving element) and the square root of this ratio (dependent upon linear density of element rows). The net result is clear: THERE IS A LARGE RECTENNA COST SAVING POSSIBLE BY UTILIZATION OF MORE DIRECTIONAL RECEIVING ELEMENTS LIKE YAGI-UDA ELEMENTS. In a typical SPS rectenna there would be $\sim$ 75 km^2 area, so that a cost reduction of $\$1/m^2$ is equivalent to a 75 million dollar reduction in capital costs. Thus savings of 300 to 450 million dollars per rectenna may be possible with the more directional Yagi-Uda element (capital costs in 1978 dollars).

The comparison between conventional construction and printed circuit implementation is less apparent. The printed circuit estimates are based upon less detailed design, but these results do not indicate a substantial reduction with printed circuit implementation. Only if socket and DC buss bar cost can be reduced will a large cost advantage result. These may be possible with careful structural designs requireing less material usage and low cost manufacturing, 5 mm diameter aluminum buss bars being assumed in our work. However, the conversion efficiency of printed circuit implementations will be somewhat lower, so baseline construction definitely seems preferred.

We have shown that more directional receiving elements are expected to lower rectenna costs in free-space microwave power transmission systems such as the SPS where the microwave power beam is relatively stationary with respect to the rectenna. Yagi-Uda receiving elements are considered most desirable when moderate gains of perhaps 8 to 14 dB (with respect to an isotropic radiator) are optimum. Yagi-Uda antennas become undesirably awkward at higher gain, and alternatives such as short backfire antennas should be considered. However it is believed that higher gain may result in unrealistically stringent power beam-rectenna alignment requirements in the SPS.

References

1. R. J. Gutmann and J. M. Borrego, "Solar Power Satellites Rectenna Design Study: Directional Receiving Elements and Parallel-Series Combining Analysis", Rensselaer Polytechnic Institute Report under Contract NAS9-15453 with NASA Johnson Space Center, December 1978.

2. R. J. Gutmann and J. M. Borrego, "Power Combining in an Array of Microwave Power Rectifiers", IEEE Trans. Microwave Theory and Techniques, MTT-27, December 1979.

3. R. J. Gutmann and R. Gworek, "Yagi-Uda Receiving Elements in Microwave Power Transmission System Rectennas", Journal of Microwave Power, 14, September 1979.

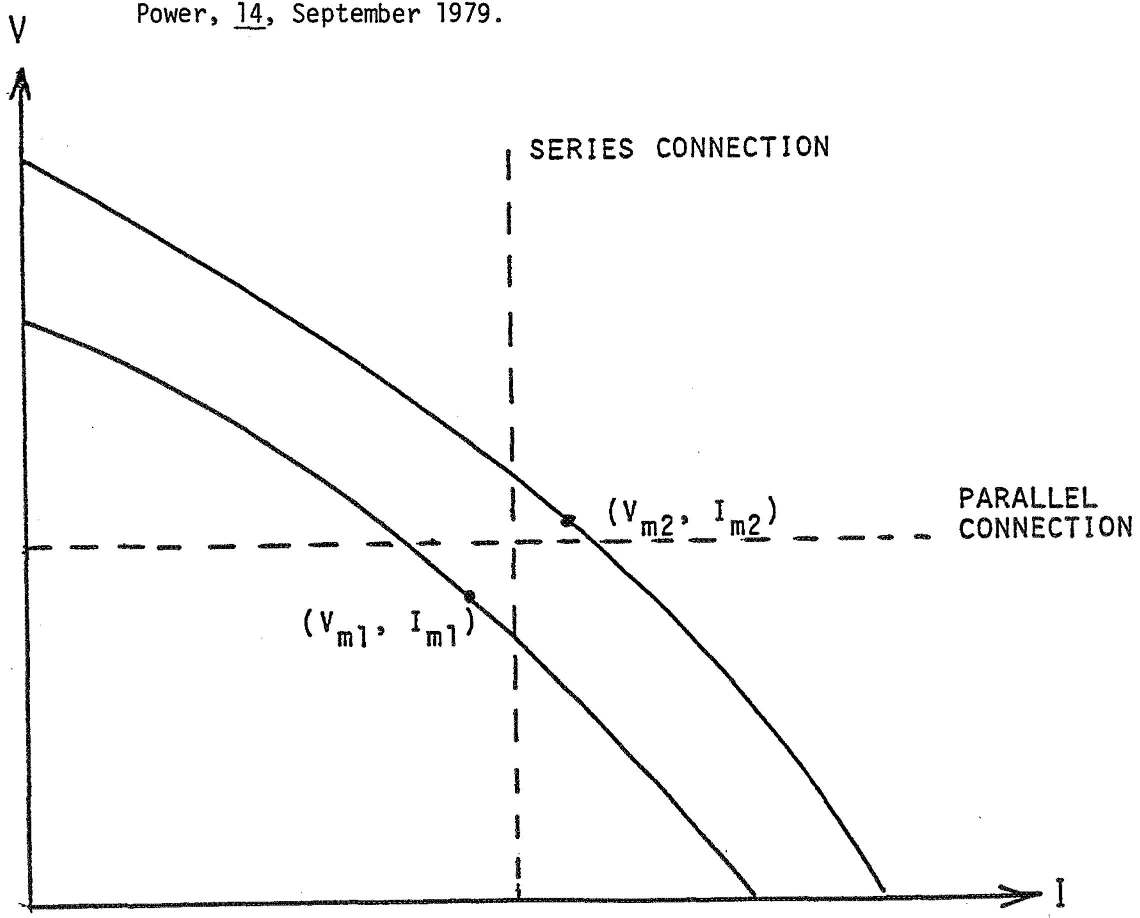

Figure 1 Output Load Line for Two Different Rectifiers

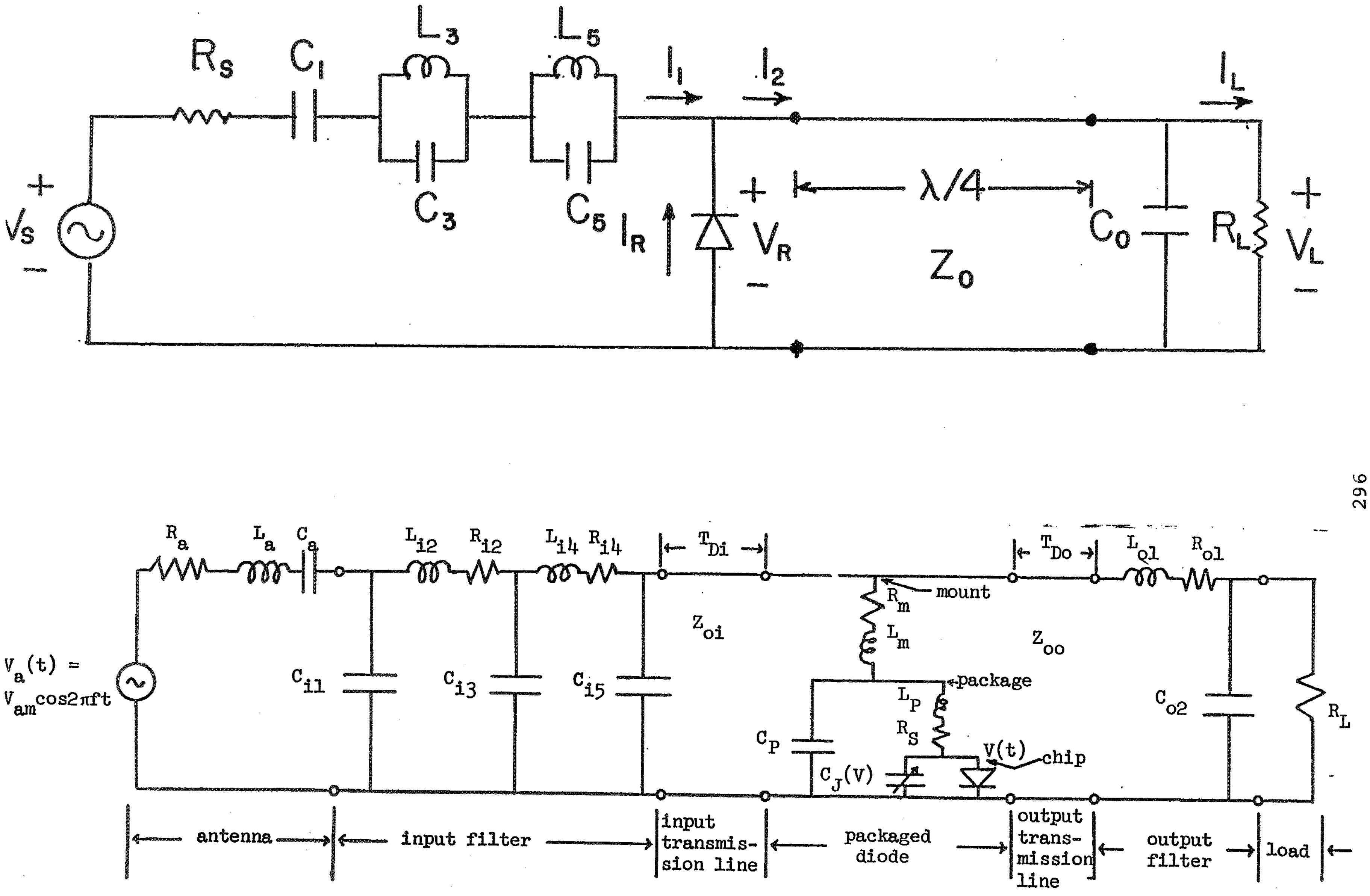

Figure 2 Equivalent Circuit Models for Microwave Rectifier
(A) Ideal Circuit Model
(B) Realistic Circuit Model of Baseline Rectifier

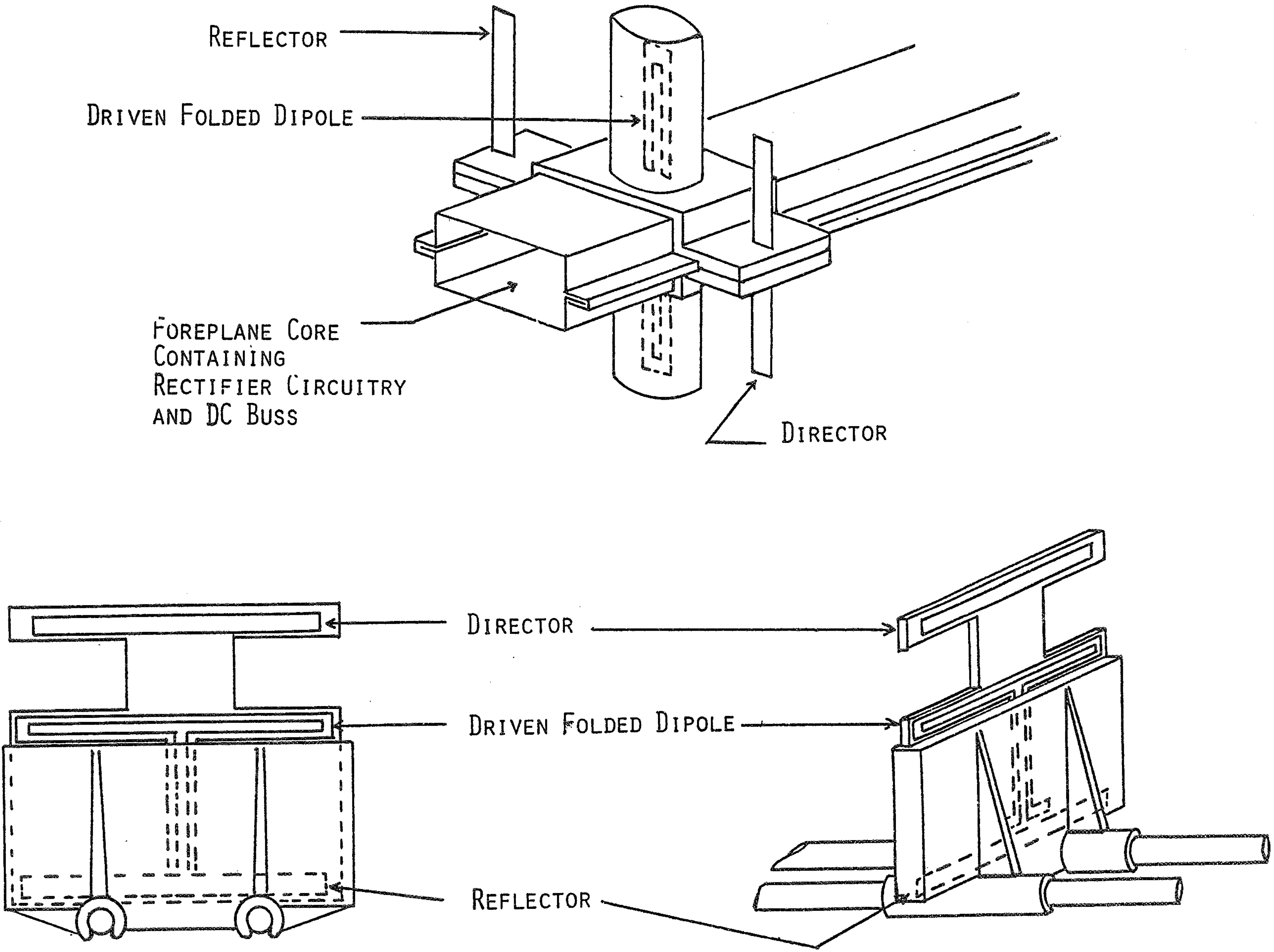

Figure 3 Three Element Yagi-Uda Receiving Array
(A) Baseline Construction
(B) Printed Circuit Construction

Table I

Expected Optimal Performance of Yagi-Uda Receiving Elements

	Gain (wrt Isotropic) dB	F/B Ratio dB	Receiving Element Reduction Factor*
3 Element-Low F/B ratio	11	5	2.82
3 Element-Moderate F/B ratio	10	15	2.24
3 Element-High F/B ratio	8.5	25	1.58
6 Element-Low F/B ratio	14	5	5.62
6 Element-Moderate F/B ratio	13	15	4.47
6 Element-High F/B ratio	11.5	25	2.82

* Relative to 6.5 dB Half-Wave Dipole Separated by $.20\lambda$ from a Conducting Ground Plane

A. Printed Circuit Board Implementation

(costs are given in $\$/m^2$)

	Half-wave Dipole with ground plane	3 element Yagi		6 element Yagi without ground plane (average size)
		with ground plane	without ground plane	
Element Density ($\frac{\text{elem.}}{m^2}$)	192	81	123	57
Socket	$ .92	$ .39	$1.12	$ .52
DC buss bar	2.78	1.81	2.23	1.55
Printed Circuit Board	.24	.24	.42	.44
Ground Plane	1.91	1.91	.00	.00
Cost/m^2	$5.85	$4.35	$3.77	$2.51
Diodes at $.01 each	$1.92	$ .81	$1.23	$ .57
Total Cost/m^2	$7.77	$5.16	$5.00	$3.08

B. Conventional Type Construction

(costs are given in $\$/m^2$)

	Half-wave Dipole with ground plane	3 element Yagi		6 element Yagi without ground plane
		with ground plane	without ground plane	
Element Density ($\frac{\text{elem.}}{m^2}$)	192	81	123	57
Foreplane Core	$3.13	$1.47	$2.09	$1.09
Aluminum Shield/ Structural Member	2.14	1.40	.92	.64
Yagi-Uda Additions	.00	.30	.71	.76
Ground Plane	1.91	1.91	.00	.00
Cost/m^2	$7.18	$5.08	$3.72	$2.49
Diodes at $.01 each	1.92	.81	1.23	.57
Total Cost/m^2	$9.10	$5.89	$4.95	$3.06

Table 2 Rectenna Cost Estimates (excluding rectenna frame)