Effective Phase-Shifter Cost as a Selection Criterion

RONALD W. LONG

(Invited Paper)

***Abstract*—In order to select a phase shifter for a given application, it is necessary to weigh a number of performance factors such that the device selected will result in the lowest overall system cost. This may be accomplished by defining an effective phase-shifter cost in terms of the initial cost of the phase shifter and driver, and dollar factors resulting from insertion loss, phase error, and quantization level.**

NO universal "best" phase shifter or phase-shifter type exists and a selection must be made in the context of the system application. Particularly in contemporary system designs, cost is a primary selection criterion that is used to set the performance requirements as well as to select the phase-shifter type. The discussion that follows develops the concept of effective phase-shifter cost to serve this selection criteria. The frame of reference of the discussion is the application to a ground-based phased array system; specifically where the power-aperture trades are not bounded by physical constraints such as they are in an airborne application. The extension of the approach to other system applications will be seen to be possible by simply considering the size constraint as an economic penalty of nonoptimum design.

Phase-shifter selection and specification is a subset of the problem of power × aperture optimization. The optimum power × aperture tradeoff and phase-shifter selection specification must be done iteratively due to the interaction of the phase-shifter cost with element cost and thus with selection of the optimum number of array elements to minimize the total system cost. The power × aperture tradeoff is simply a matter of maintaining a constant power × aperture product (for the search function) in order to hold system performance constant while determining total system cost. If the primary system function is track rather than search, and the track performance is specified in terms of equal azimuth and elevation errors, the power × aperture-cubed product must be maintained constant in parametric studies. For the purpose of this discussion, it is assumed that the power × aperture-squared product is maintained constant, a situation generally compatible with performing a mix of search and track functions.

For the purpose of illustration, the cost of RF transmit power at L band is assumed to be \$10/W and the cost per element is assumed as \$200. The cost per watt includes power supplies, power amplifiers, and modulation equipment. The cost of the element includes the element, supporting structure, phase shifter, and driver, plus phase-shifter performance allocable costs to be investigated. These costs are hypothetical, do not include nonrecurring engineering costs, and no claims of reality or achievement are made.

Using these cost factors, the total of the array cost and the cost of power is plotted in Fig. 1 for a power × elements-squared product of 10^{13}. The minimum total cost is predictably at 10 000 elements and 10 W/element; this results in a \$100/element cost of RF power as compared to the \$200 element cost. This minimum cost point is only dependent on the use of the power × aperture-squared constraint and not on the arbitrary product selected for the illustration. Thus, if the search performance had been used for the constraint, minimum cost would have been achieved where the cost of RF power per element equaled the element cost. Similarly, when the trade is constrained only by track performance, minimum cost occurs when the RF power cost per element is one-third the element cost. Power aperture trades have been well covered in the literature [4]–[6].

With the assumed cost of RF power and the selection of the average power per element to minimize total system cost as given in Fig. 1, the various phase-shifter performance parameters may be interpreted in terms of an equivalent cost factor:

$$\begin{array}{c}\text{differential transmitter}\\ \text{cost per element}\end{array} = \begin{array}{c}\text{cost}\\ \text{per watt}\end{array} * \begin{array}{c}\text{round trip}\\ \text{loss factor}\end{array} * \begin{array}{c}\text{average power}\\ \text{per element.}\end{array}$$

The effective power lost (in two-way transmission) is priced at \$10/W. Thus the effective cost of the insertion loss (including mismatch effects) varies from 0 to \$70 for losses increasing up to 1.2 dB as illustrated in Fig. 2. A typical loss of 0.65 dB costs \$35/element in the context of this analysis.

The phase quantization error may be costed by the same relationship for the case where digital control is used. In Table I, the two-way loss factor is developed from Allen [1] for the quantization loss in terms of the number of phase control bits (P); this loss factor has been adjusted for transmit–receive operation. The resulting loss factor is priced at \$10/W to arrive at cost factors that range from \$45.30 for a two-bit unit to \$2.60 for a four-bit unit as tabulated in Table I. While the \$34.80 cost reduction

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The author is with the Ground Systems Group, Hughes Aircraft Company, Fullerton, Calif. 92634.

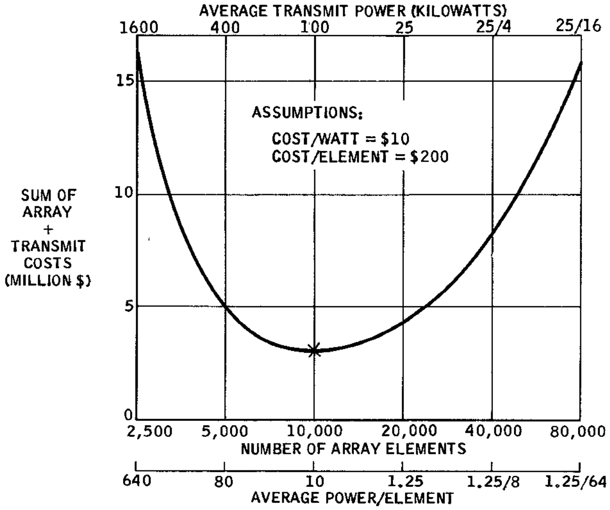

Fig. 1. Power × aperture cost tradeoff for constant power × aperture squared. Minimum cost for this constraint occurs when the cost of RF power per element is one-half the element cost.

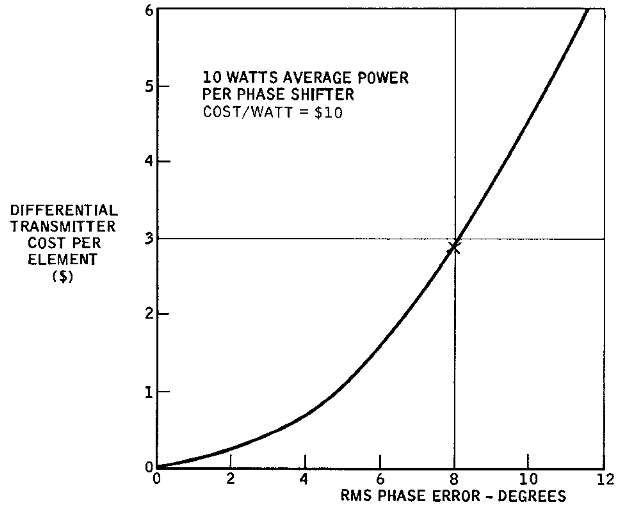

Fig. 3. Effect of phase-shifter random phase error on differential transmitter cost. The cost of typical phase error induced losses is small.

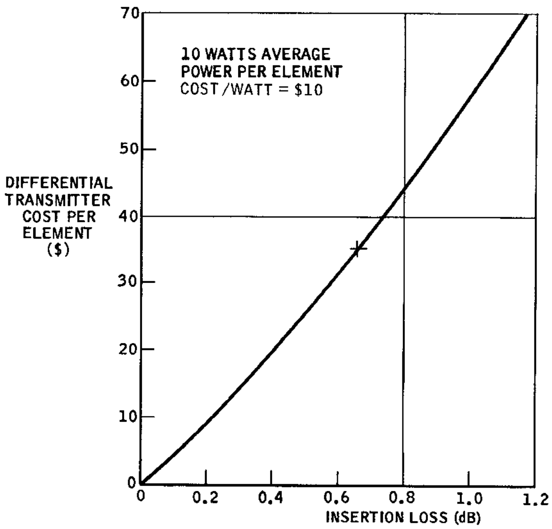

Fig. 2. Effect of phase-shifter insertion loss on differential transmitter cost per element. The $35 cost of a nominal 0.65-dB loss is a significant part of the overall phase-shifter cost.

TABLE I
EFFECT OF PHASE-SHIFTER QUANTIZATION ERROR ON DIFFERENTIAL TRANSMITTER COST

NUMBER OF BITS, P	RMS ERROR IN DEGREES	TWO-WAY LOSS FACTOR	△ COST
2	26	0.453	$45.30
3	13	0.105	$10.50
4	6.5	0.026	$ 2.60

Note: The use of a fourth phase-shifter bit to reduce cost is dependent on the cost of the additional bit plus its driver being less than $10.50–$2.60. Two-way loss factor $= (1 + \pi^2/3/2^{2P})^2 - 1$.

achieved in going from a two-bit unit to a three-bit device is usually profitable, the $7.90 reduction will seldom pay for the fourth bit of a digital phase shifter plus the associated drive circuitry. The details of this trade are not further considered here. Sidelobe and angular error specifications must, of course, be considered as their requirements may be more constraining on the selection of the number of phase-shifter bits and phase error. In designs where clutter in sidelobe areas is a limiting factor, a cost factor related to clutter level due to sidelobes may be developed.

The pricing of the loss effect resulting from random phase error in the phase shifter is illustrated in Fig. 3 as a function of a random phase error of $\theta°$ up to 12°. The loss factor due to an element rms phase error of (ϵ) radians may be approximated as $3/4(\epsilon^2)$ for a nominal element gain of 6 dB. For the small values of (ϵ) considered here, the two-way loss factor is satisfactorily approximated as $3/2(\epsilon^2)$. Using this loss factor in the differential transmitter cost relationship provides the data plotted in Fig. 3 for the sample case. An 8° rms phase error is seen to cost $2.90 at $10/W. This relatively small cost factor usually means that phase error is constrained by specification of system angular error or sidelobe level. The curve in Fig. 3 is the basic information required to perform a trade of cost of holding to an error specification versus the cost of the phase error.

The effective system cost of the phase shifter and driver is shown in Fig. 4 for a three-bit digital phase shifter with a 0.65-dB one-way loss and an 8° rms phase error. The phase-shifter initial cost has been assumed to be $70 and its driver $60. The total effective phase-shifter cost is seen to be $178 and Fig. 4 shows the relative magnitudes of the various cost factors for comparison. The cost of the radiating element, feed cost, and structure costs would bring the overall element cost to somewhat above the $200 figure initially assumed in the power × aperture-squared tradeoff; the degree depending on the type of feed and structural requirements. If the overall element cost is significantly different than that assumed, it would be necessary to iterate to further minimize the total system cost. The broadness and flatness of the minimum cost illustrated in Fig. 1 for sensible ranges of element

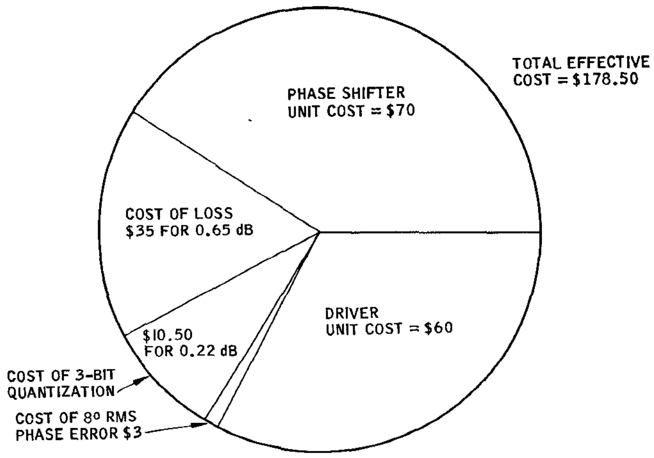

Fig. 4. Distribution of total effective cost for the phase shifter and driver in the text example. The effective cost of the phase-shifter imperfections amounts to 37 percent of the cost of the phase shifter and driver for this case.

numbers allows a satisfactory design to be achieved with few iterations.

Many times, the phased array designer is faced with a problem of selecting between diode and ferrite phase shifters having different initial costs and insertion losses. The effective system cost as outlined here provides a quantitative way of measuring the performance factors in terms of dollars as a common denominator. Similar approaches may be applied to the case where the aperture is constrained so that a nonoptimum power × aperture trade is dictated. This will generally result in a higher power per element and thus place a much higher premium on the insertion loss and other loss relatable performance parameters.

Evaluation of the effective cost of phase-shifter loss factors based on differential transmitter cost is valid for the optimum design case where it costs just as much to improve performance by a decibel in either transmitter or array. In the nonoptimum design case where the aperture is limited, it would be less costly to make up for a loss by an increase of array size, but that is not possible, so it is still valid to use the differential transmitter cost. If a nonoptimum design is forced in which the transmitter is too small, it would be appropriate to evaluate phase-shifter losses in terms of differential array costs.

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Comments on the Design and Manufacture of Dual-Mode Reciprocal Latching Ferrite Phase Shifters

CHARLES R. BOYD, JR., SENIOR MEMBER, IEEE

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***Abstract*—The design principles for dual-mode reciprocal latching ferrite phase shifters are relatively well understood at present. Discussions of a few selected topics not previously studied are presented in this paper. A tradeoff analysis is carried out for *X*-band units to show the interrelation between phase-shifter weight and insertion loss. An interesting consequence of this analysis is the theoretical prediction of an optimum range of values for the saturation moment of the ferrite material. Switching energy in the presence of shorted-turn damping is also analyzed and related to the geometry and hysteresis loss of the ferrite material. Finally, a discussion of manufacturing considerations and unit cost at high rates of production is carried out. The major conclusion is that unit cost levels approaching $10.00 are possible for a production run sufficiently large to justify the substantial cost of engineering and tooling for high rates of manufacture.**

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The author is with the Microwave Applications Group, Chatsworth, Calif. 91311.

INTRODUCTION

PHASED-ARRAY antenna needs have stimulated a wide variety of exploratory ferrite phase-shifter work in recent years. The main objectives of this work have