Chapter 4
Overview of Arraying Techniques

There are five basic signal-processing schemes that can be employed to combine the output of separate antennas that are observing a spacecraft-type signal. These schemes have come to be known as: (1) full-spectrum combining (FSC), (2) complex-symbol combining (CSC), (3) symbol-stream combining (SSC), (4) baseband combining (BC), and (5) carrier arraying (CA). Mileant et al. [1] have analyzed the performance of these techniques and have discussed the complexity of the reception of spacecraft signals. Their analysis will merely be summarized here but is presented in detail in Chapter 6. It should be noted that four of these schemes (CSC, SSC, BC, and CA) work *only* with a signal that has well-defined modulation characteristics. They utilize the fact that the signal source has a unique spectral characteristic and process those signals accordingly. The first scheme, FSC, works equally well with signals that are unknown or noise-like, as in the case of astronomical radio quasars.

All of the arraying techniques fall in the general category of signal processing. The overall SNR is determined by the capture area of the antennas and the thermal noise generated by the first amplifier. In a typical signal-flow diagram, the low-noise amplifier is followed by open-loop downconverters (typically two stages) that heterodyne the portion of the spectrum occupied by the spacecraft signal to a frequency that can be easily digitized. Digital signal-processing techniques are then employed, and ultimately an estimate is made of the data bits impressed on the carrier at the spacecraft. The data are then delivered to the project that operates the spacecraft. Although the front end of the signal-flow diagram is identical for all of the arraying techniques, and the ultimate goal is the same, the details of implementation vary. This results in very different capital investment and operations costs. These differences make it extremely difficult to unambiguously determine a “best” arraying technique. The following sections provide general characterizations of these techniques.

4.1 Full-Spectrum Combining (FSC)

The block diagram of FSC is shown in Fig. 4-1 and has been analyzed by Rogstad [2]. In FSC, the intermediate frequency (IF) signals from each antenna are transmitted to the combining site, where they are combined. To ensure coherence, the signals must be delayed and phase adjusted prior to combining. An estimate of the correct delay and phase normally is accomplished by correlating the signal streams.

The primary advantage of FSC is that it can utilize the spectral characteristics of the signal source but does not crucially depend on them, i.e., the received spectrum can be filtered if the spectral characteristics are known or accepted in total if the spectrum is unknown or noise-like. FSC can be used when the carrier is too weak to track or is not possible to track with a single antenna. In this case, the gross relative delays and phases between antennas are determined a priori from geometry calculations. Then the residual relative delays and phases are determined by cross-correlation of the signals from each antenna. These delays and phases are used to correct the antenna IF signals, and then they are combined.

One cost driver with FSC arises when the signal spectrum is unknown or noise-like. The entire signal bandwidth must then be transmitted to the combining site. If the transmission is analog, then the link must have high phase stability and low dispersion in order to maintain phase coherence at the radio frequency. If the link is digital, it must have relatively large bandwidth (assuming multibit digitization). Depending on the compactness of the array

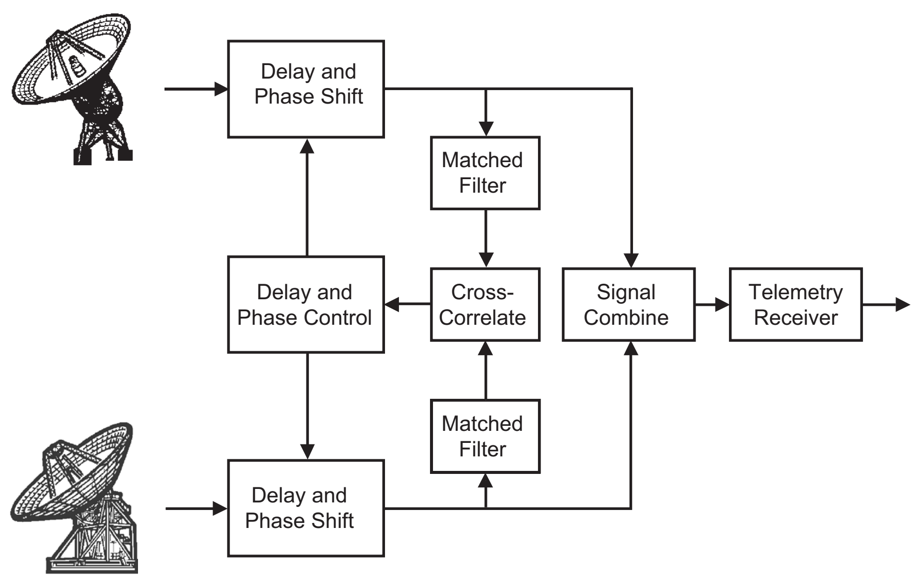

Fig. 4-1. Full-spectrum combining.

and the cost to install fiber-optic cabling, this may or may not be a real disadvantage.

4.2 Complex-Symbol Combining (CSC)

The block diagram of CSC is shown in Fig. 4-2. The intermediate frequency (IF) signal from each antenna is fed to a receiver, where it is open-loop carrier tracked using the best available carrier predicts. If this tracking is kept within a frequency error much less than the symbol rate, it can then be subcarrier demodulated (if used), and then symbol synchronization (sync) can be performed. These complex symbols (because of the unlocked carrier) are sent to the combining site, where they are combined. To ensure coherence, the signals must be phase adjusted prior to combining. An estimate of the correct phase normally is accomplished by correlating the various signal streams.

An advantage of this technique is that the data are transmitted to some central combining site at only slightly higher than the symbol rate. The symbol rate is some multiple of the data rate, dependent on the coding scheme, and for most applications is relatively modest. The rate at which data are communicated to a central site is an important cost consideration since most users want their data in real time. However, as with FSC, there are stringent requirements on instrumental phase stability.

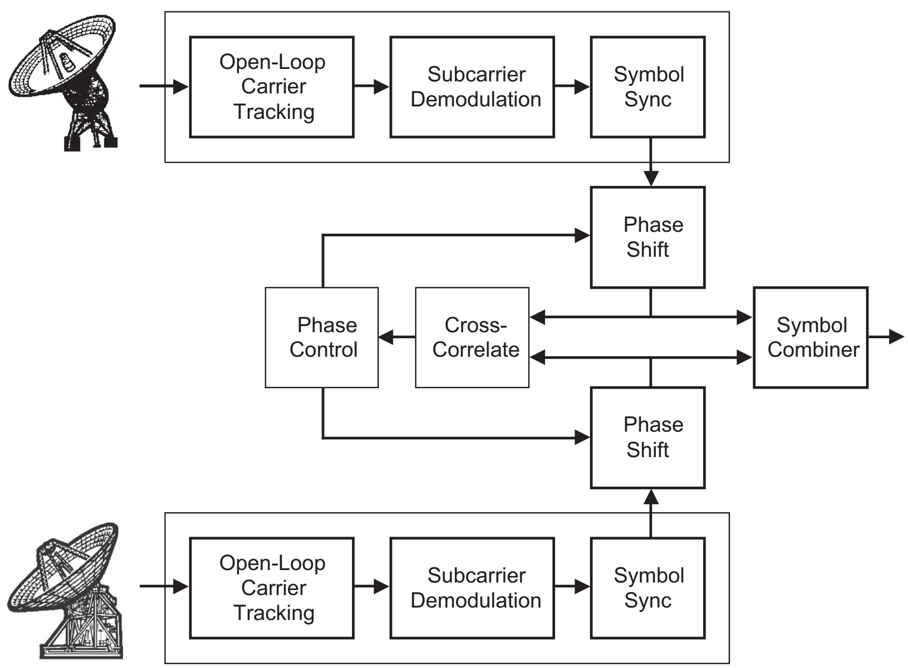

Fig. 4-2. Complex-symbol combining.

The disadvantages of CSC stem from the requirement that, like SSC, a carrier, subcarrier (if used), and symbol-tracking device must be provided for each antenna. The fact that the carrier-tracking loops are left open lessens the demand for an SNR as high as the one in the SSC case (see the next section).

4.3 Symbol-Stream Combining (SSC)

The block diagram of SSC is shown in Fig. 4-3. The signal from each antenna is used by the receiver to track the carrier (and subcarrier, if present) and to perform symbol synchronization. Once symbol synchronization is achieved, it is relatively straightforward to delay one data stream relative to the other in order to align the symbols in time. The symbols are then combined with the appropriate weights to form an estimate of a "soft" symbol, i.e., the raw telemetry data, before a decision is made as to whether a given bit (derived from the symbols through data decoding) is +1 or –1.

One advantage of this technique is that the data are transmitted to some central combining site at the symbol rate. The symbol rate is some multiple of the data rate, dependent on the coding scheme, and for most applications is relatively modest. The rate at which data are communicated to a central site is an important cost consideration since most users want their data in real time. In addition, there are no stringent requirements on instrumental phase stability.

The disadvantages of SSC stem from the requirement that a carrier, subcarrier (if used), and symbol-tracking device be provided for each antenna. Given that the cost per unit of complexity for digital electronics is rapidly decreasing with time, it may well be possible to build a "receiver on a chip" for just a few dollars, so the cost impact may be negligible. However, performance is another matter. The fact that all of the tracking loops must be locked demands that we have high loop SNR. This is achieved through a combination of high signal strength and small loop bandwidth. For small antennas with inherently low signal strength, the implied narrow loop bandwidth could become very difficult to obtain, and the technique could become impractical.

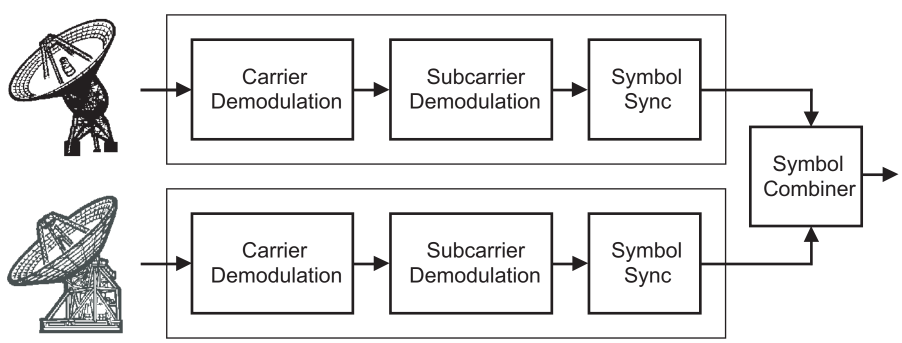

Fig. 4-3. Symbol-stream combining.

As a side note here, loop bandwidth can be thought of as inversely related to the amount of signal averaging that goes on within a phase-locked loop to obtain the error signal used to lock the loop. A narrow loop bandwidth means more averaging or integration in time, and therefore more SNR to lock. However, if the incoming signal is inherently unstable and varies significantly in frequency (phase noise), then the loop bandwidth must be kept large enough to maintain track. This trade-off determines the performance of the loop.

4.4 Baseband Combining (BC)

The block diagram of BC is shown in Fig. 4-4. In BC, the signal from each antenna is carrier locked. The output of the carrier loop is at a baseband frequency and consists of the subcarrier harmonics. The baseband signal is digitized, delayed, weighted, and then combined. The delay offsets usually are obtained by cross-correlating the baseband signals from the various antennas. The combined signal is used to achieve subcarrier lock and symbol demodulation. This technique collapses to SSC if no subcarrier is used.

In effect, the carrier signal from the spacecraft is used as a phase reference so that locking to the carrier eliminates the radio-frequency phase differences between antennas imposed by the propagation medium. The information bandwidth containing the subcarrier and its harmonics is relatively narrow and can be heterodyned to baseband. The low baseband frequency then imposes instrumental stability requirements that are relatively easy to compensate. The baseband data that must be transmitted to a central combining site contain all of the significant subcarrier harmonics and therefore can be more of a cost consideration than with SSC.

The disadvantage of this technique is that carrier lock is required on the signal from each individual antenna. As the antenna diameter decreases, the carrier SNR is reduced and must be compensated for either by a longer

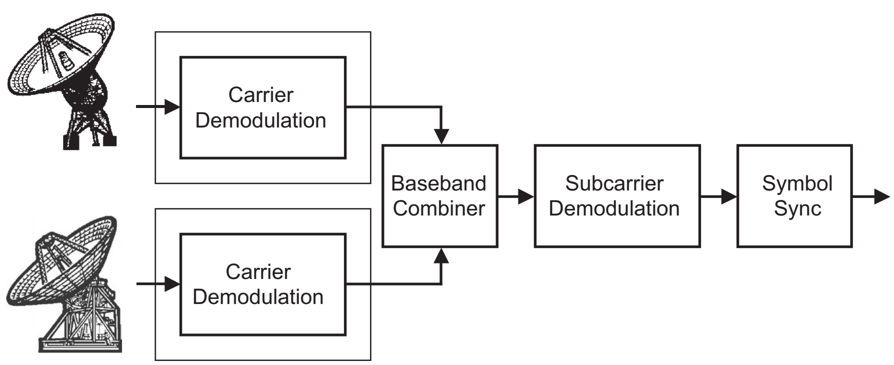

Fig. 4-4. Baseband combining.

integration time or by having the spacecraft increase the amount of power in the carrier. Halving the carrier SNR implies twice as much integration time (or, equivalently, a narrower bandwidth in the phase-locked tracking loop), which sometimes is possible but cannot be carried out indefinitely because of lack of signal stability due either to the transmitter, receiver, or propagation medium. If the spacecraft is programmed to increase the carrier power, there is less power available for the data, and the data rate must be reduced.

4.5 Carrier Arraying (CA)

The block diagram of CA is shown in Fig. 4-5. In carrier arraying, the individual carrier-tracking loops on each array element are "coupled" in order to enhance the received carrier SNR, thereby decreasing the "radio" loss due to an imperfect carrier lock on a single antenna [3].

In effect, all of the carrier-tracking devices are used to arrive at a "global" estimate of the best carrier synchronization. Alternatively, a single large antenna can provide carrier-lock information to a number of smaller antennas. The actual combining then can be done either at an intermediate frequency or at baseband, with the attendant advantages and disadvantages of each. However, carrier-lock information must be transmitted to a central site, and the global solution must be transmitted back to each antenna. For antennas separated by a large distance, the carrier-lock information must be corrected for different geometries. Estimates of the delay offsets normally are accomplished by correlating the signal streams from the various antennas.

Table 4-1 summarizes the requirements for each of the five types of arraying. Some of these are discussed in more detail in Chapter 6.

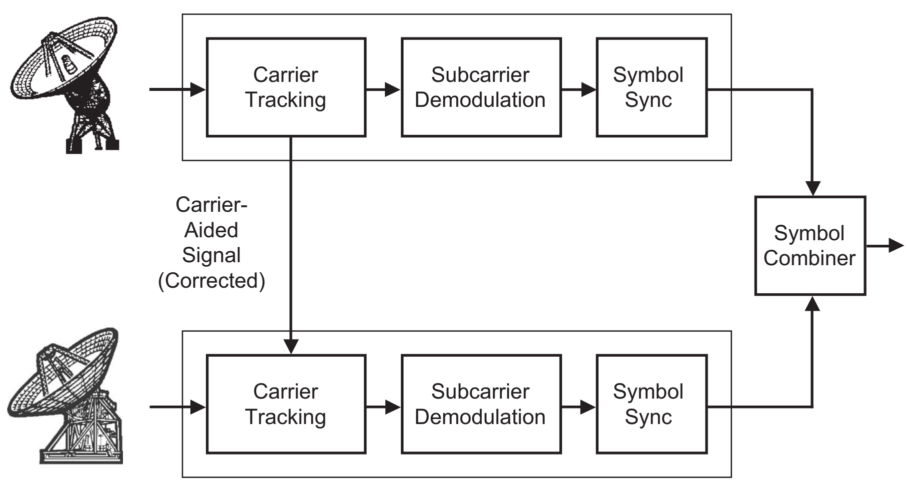

Fig. 4-5. Carrier arraying.

Table 4-1. Summary of requirements for combining techniques.

Requirements	FSC	CSC	SSC	BC	CA
Carrier lock at individual antennas	No	No	Yes	Yes	Yes
Bandwidth into combiner (in units of the symbol rate)	~10	~1	~1	~10	~1
Phase stability to antennas	High	High	Low	Low	High
Dependent on signal spectrum	No	Yes	Yes	Yes	Yes

References

[1] A. Mileant and S. Hinedi, "Overview of Arraying Techniques in the Deep Space Network," *The Telecommunications and Data Acquisition Progress Report 42-104, October–December 1990*, Jet Propulsion Laboratory, Pasadena, California, pp. 109–139, February 15, 1991.

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[2] D. H. Rogstad, "Suppressed Carrier Full-Spectrum Combining," *The Telecommunications and Data Acquisition Progress Report 42-107, July–September 1991*, Jet Propulsion Laboratory, Pasadena, California, pp. 12–20, November 15, 1991. http://ipnpr.jpl.nasa.gov/progress_report/

[3] S. A. Butman, L. J. Deutsch, R. G. Lipes, and R. L. Miller, "Sideband-Aided Receiver Arraying," *The Telecommunications and Data Acquisition Progress Report 42-67, November–December 1981*, Jet Propulsion Laboratory, Pasadena, California, pp. 39–53, February 15, 1982.

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