Design Considerations for a Wearable Anti-Jam GPS Antenna

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***Abstract*— System constraints for a wearable anti-jam GPS antenna are explored, including antenna size, design of textile-integrated wearable antennas, null steering algorithms to maximize anti-jam performance, system power consumption, and data rate limitations into a GPS receiver. A textile-integrated pin-fed GPS patch antenna is analyzed through simulation and measurement and found to perform reasonably well, though with a size that may be restrictive for employing an anti-jam antenna on the human body. A dual polarized null steering algorithm is explored through analytical simulation to assess its ability to increase the anti-jam performance of a controlled reception pattern array without increasing the overall size of the array. Finally, overarching limitations for man-portable anti-jam GPS systems such as RF front end power consumption and data rate limits of the interface between an anti-jam module and a standalone GPS receiver are discussed and related to both antenna design and null-steering algorithm selection.**

***Index Terms*— Antenna, GPS, anti-jam, adaptive array**

I. INTRODUCTION

There is strong interest in the development of new navigation technologies that can provide accurate and uninterrupted position, navigation and timing information in crowded and contested electromagnetic environments. An essential element in such a navigation system is the GPS receiver antenna, which must be designed to maintain a stable link with visible GPS satellites while providing robust protection against hostile jamming signals.

GPS signals are transmitted as right-hand circular polarization (RHCP) signals at L1 (1575.42 MHz) and L2 (1227.60 MHz) carrier frequencies from a set of orbiting satellites located at an altitude of ~20,200 km. Since the GPS signals are transmitted at only ~25 W, the received signal at a typical GPS receiver is significantly below the noise floor, on the order of –155 to –160 dBW [1]. This results in a carrier-to-noise ratio (C_S/N_0) within the receiver that is particularly susceptible to RF interference (RFI). If the overall noise level is increased enough by in-band interferers such that C_S/N_0 surpasses a certain threshold (e.g. 28 dB/Hz), jitter within the tracking phase locked loop (PLL) of the GPS receiver can cause phase errors that degrade accuracy and disrupt signal acquisition and/or tracking of the carrier signal.

Typically, fixed bandwidth front-end radio RF filters are used to reject out-of-band jammers and general low-power RFI. For more robust filtering against continuous wave (CW) tone jammers, intermediate frequency (IF) adaptive notch filters can also be employed. These techniques yield between 15 and 30 dB in jammer suppression with minimal effect on the GPS signal, which is enough to mitigate the effects of moderate power/distance jammers (e.g. 1 W source at 10 km) but still leaves the receiver susceptible to the effects of high-power and/or close distance jammers.

For wearable GPS receivers, anti-jam solutions are constrained by extreme size, weight and power limitations. Many digital signal processing techniques that have been developed for reducing interference signals must be eliminated from consideration since they require a system that far exceeds the size and power limitations available to the mobile human platform. A controlled reception pattern array (CRPA) [2], which employs spatial filtering of received RF signals, is a particularly efficient anti-jam solution that can be tailored to meet the limitations of a wearable system.

This paper will discuss some of the system constraints that should be considered when designing a wearable GPS CRPA.

II. CONTROLLED RECEPTION PATTERN ARRAY OVERVIEW

A basic CRPA, shown in Fig. 1, is comprised of an array of GPS antennas that leverages adaptive array theory to steer the nulls of the reception pattern toward the direction(s) of jamming signals [3].

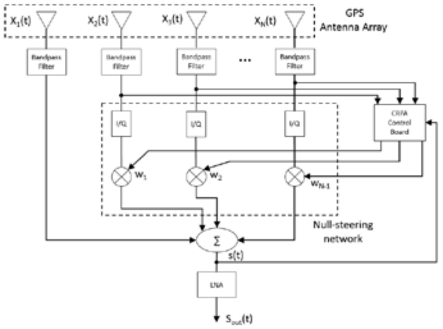

Fig. 1. Diagram of basic controlled reception pattern array (adapted from [2].)

All signals received by the antenna array are passed through the system RF front end, which provides initial filtering of out-of-band signals, to the GPS receiver, where null-steering algorithms are employed to adjust the array's reception pattern accordingly and spatially filter out undesired in-band signals. These algorithms operate by calculating amplitude and phase adjustment weight values for each array element using a basic optimization method, such as the minimum mean square error (MMSE), that attempts to minimize jammer signal power at the combined received output signal, and at the same time keep one of the array elements constant to guarantee the reception of valid GPS signals. The received RF signals from the array elements, $X_1(t)$ to $X_N(t)$, are mixed with these amplitude and phase weights, w_1 to w_{N-1}, and summed to produce a reception pattern for the array with nulls steered in the direction(s) of the jamming signals. An N-element RHCP CRPA has enough degrees of freedom to mitigate N-1 number of interferers.

III. ANTENNA DESIGN

With the human body as a platform, space for an anti-jam antenna array is significantly constrained and likely confined to a total size of less than 5 x 5 x 1". Since the free space wavelength is 7.5" at L1 band and 9.6" at L2 band, the number of array elements that can be employed in such a small area is extremely limited, even if size reduction techniques are considered. Multiple sub-arrays may be employed at different points on the body, however the electrically large spacing between sub-arrays may introduce grating lobes and present significant challenges for implementing anti-jam null steering.

GPS CRPA research to date has mainly focused on minimizing the size of planar, vehicle-mounted GPS CRPAs, typically with some form of dielectric loading [4], [5]. While very compact in diameter, these CRPA designs rely on rigid, heavy and/or thick dielectric substrates that do not possess desired characteristics for a wearable system such as conformability, flexibility and durability. A conformal externally-mounted flexible antenna or textile-integrated antenna is needed to meet the needs of a wearable CRPA.

A conductive fabric pin-fed patch antenna, shown in Fig. 2, was designed and simulated using the FEKO full-wave electromagnetic simulation software to examine the feasibility of a textile-integrated wearable CRPA antenna element.

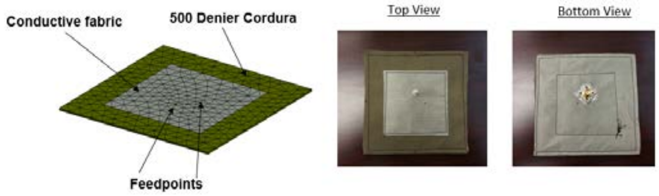

Fig. 2. Fabric patch antenna FEKO model and fabricated prototype.

The antenna was fabricated on a 500 denier Cordura fabric substrate. A single layer of this fabric is only ~16 mil thick, so three layers were sewn together to form a substrate with total thickness of ~48 mil in order to increase the bandwidth of the antenna. The fabric was modeled as a thin slab with $\varepsilon_r = 1.9$, $\mu_r = 1$, and $\tan(\delta) = 0.0098$. *Shieldex* conductive fabric, comprised of three layers of Nylon fabric metallized with nickel, tin and silver, was used as the 2.6" x 2.6" patch and 5" x 5" ground plane and had a measured sheet resistance of approximately 0.02 Ω-sq. This material was modeled as a 4 mil thick conductive sheet with $\sigma = 5e5$ S/m.

The simulated and measured reflection coefficient data is shown in Fig. 3. The measured resonant frequency is at ~1.575 GHz (L1 GPS band) and agrees well with the simulated result. The measured E-plane and H-plane radiation pattern data at 1.575 GHz is shown in Fig. 4. The realized gain at broadside is ~1.2 dBi, which is 0.3 dB lower than the simulated estimate of 1.5 dBi and within measurement error tolerances.

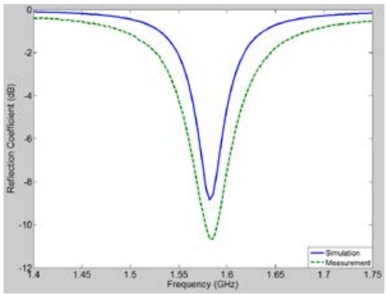

Fig. 3. Reflection coefficient for textile-integrated patch antenna fabricated on Cordura fabric substrate.

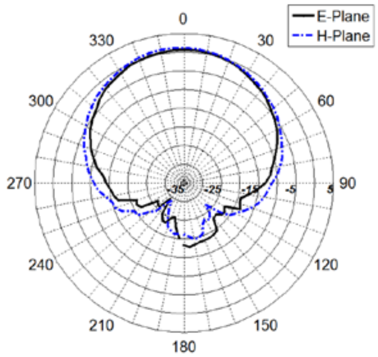

Fig. 4. Radiation pattern (f = 1.575 GHz) for textile-integrated patch antenna fabricated on Cordura fabric substrate.

This peak gain is ~4-6 dB lower than a typical metal patch antenna fabricated on a low-loss rigid substrate and demonstrates one of many design challenges associated with textile-integrated antennas. The losses associated with this low peak realized gain are likely due to the conductivity of the conductive fabric material, which is two orders of magnitude lower than that of copper ($\sigma = 5e5$ vs $5e7$ S/m), and due to the loss tangent of the fabric, which is approximately one order of magnitude higher than a typical low-loss substrate such as RT/Duroid 5870 ($\tan(\delta) = 0.0098$ vs. 0.001).

As mentioned previously, the thickness of typical fabric material is much too low to enable a large enough patch antenna bandwidth for L1 or L2 GPS. Multiple layers of fabric must be used (typically, at least 3 to 4) to meet bandwidth needs (~25 MHz). Additionally, since the dielectric constant of the Cordura fabric is only 1.9, the size of a single element designed for operation at the L1 GPS band is ~2.6" x 2.6". Thus, a four-element textile-integrated CRPA with half-wavelength element spacing would be on the order of 6.5" to 9" without any further size reduction. A flexible, low-loss, high ε_r substrate in between layers of fabric is necessary to facilitate element size reduction and enable a textile-integrated CRPA that meets the size constraints of the human body. Considering the above limitations, an externally mounted GPS CRPA comprised of a low-loss, high ε_r flexible substrate may be more efficient to fabricate compared to a fully textile-integrated CRPA.

IV. NULL-STEERING ALGORITHM

Since size constraints of the human body may severely limit the number of elements available for a wearable GPS CRPA, methods for maximizing the degrees of freedom for the CRPA should be considered. By using dual-linear polarized antennas, 3 dB of loss will be sacrificed due to polarization mismatch with an incoming RHCP GPS signal. Since the GPS signal is already well below the noise floor of a GPS receiver, this loss is minimal and recovered with relative ease. However, the degrees of freedom for an N-element dual-linear polarized CRPA is 2N −1. Thus, by employing such a design, it may be possible to nearly double the number of jammers capable of being mitigated by a CRPA without increasing its size [6].

The feasibility of this method was explored through analytical simulation of a 2x2 element L1 band CRPA, as shown in Fig. 5. The elements within the array were modeled to match the patch antenna detailed in Section III, each with horizontal and vertical polarization input ports for dual linear polarization and elements spaced a half wavelength apart (d = 3.74"). The normalized gain for each element was computed using analytic expressions derived from the cavity model for a patch antenna.

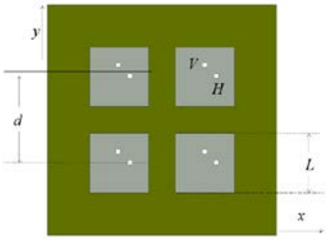

Fig. 5. Layout for a dual-polarized controlled reception pattern array.

For the simulation, the received signal prior to null steering was an 8 × 1 column vector composed of the desired GPS signal and a chosen number of statistically independent narrowband interference signals impinging on each antenna. The output of the array after null steering was a weighted sum of the received signal vector, with the weight vector calculated using the MMSE algorithm that employed a constraint vector requiring that a selected reference antenna have unity gain for incoming RHCP signals, adapted from the method described in [6]. The amplitudes for the interferences were based on a 1W transmitting antenna with 3 dBi gain located 1 km from the receiving array and transmitting either a RHCP signal or LP signal with 45° polarization angle. A comparison of satellite coverage after null steering was employed for a RHCP CRPA and a dual-linear polarized CRPA for one to ten LP and RHCP jammers is shown in Figs. 6 and 7, respectively. The box plots for each jammer count number represent the simulation results of one hundred realizations, with jammer signal directions of arrival (DOAs) selected randomly from uniform distributions of θ and φ for each realization. C_S/N_0 was calculated for GPS signals arriving from each DOA in the sky using typical GPS receiver and minimum received signal values [1]. If C_S/N_0 was above 28 dB-Hz (a typical receiver tracking threshold [1]), the GPS signal was deemed to be recoverable from that DOA. Satellite coverage was defined to be the percentage of the sky from which GPS signals were recoverable.

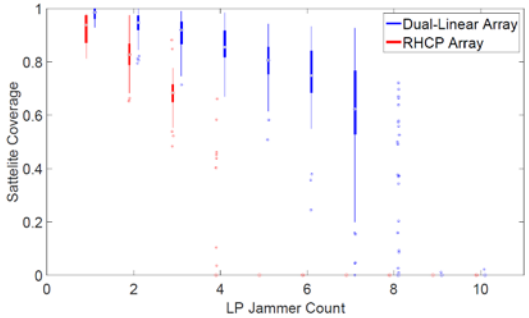

Fig. 6. Comparison of CRPA performance for multiple LP interferences.

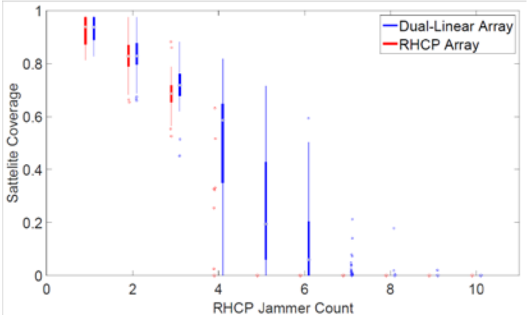

Fig. 7. Comparison of CRPA performance for multiple RHCP interferences.

TABLE I

MEDIAN GPS COVERAGE (%) FOR VARIED CRPAS & LP JAMMER COUNTS

	# of LP Jammers						
CRPA Type	***1***	***2***	***3***	***4***	***5***	***6***	***7***
Two-Element RHCP	83	0	0	0	0	0	0
Two-Element Dual LP	96	86	74	0	0	0	0
Three-Element RHCP	86	74	0	0	0	0	0
Three-Element Dual LP	97	88	78	67	56	0	0
Four-Element RHCP	94	83	68	0	0	0	0
Four-Element Dual LP	99	95	92	86	81	75	62

TABLE II

MEDIAN GPS COVERAGE (%) FOR VARIED CRPAS & RHCP JAMMER COUNTS

	# of RHCP Jammers						
CRPA Type	***1***	***2***	***3***	***4***	***5***	***6***	***7***
Two-Element RHCP	83	0	0	0	0	0	0
Two-Element Dual LP	83	47	3	0	0	0	0
Three-Element RHCP	86	74	0	0	0	0	0
Three-Element Dual LP	86	72	48	14	0	0	0
Four-Element RHCP	94	83	69	0	0	0	0
Four-Element Dual LP	94	83	72	59	19	0	0

In the case of RHCP jammers, both CRPA versions are limited to N-1 degrees of freedom and, as expected, median satellite coverage drops significantly to approximately zero beyond the case of three RHCP jammers. The RHCP CRPA sees almost no difference between RHCP and LP jammers since it can only cancel interference spatially and doesn't have the freedom to accept input signals from only one linear polarization. While the RHCP CRPA displays a severe drop in coverage when four or more LP jammers are present, the dual linear polarization CRPA can cancel out LP jammers extremely well, up to seven jammers. This is expected since the RHCP CRPA has N-1 degrees of freedom and the dual linear polarization CRPA has 2N-1 degrees of freedom.

The impact of CRPA element number on satellite coverage for one to ten LP and RHCP jammers is shown in Tables I and II, respectively. The degrees-of-freedom limitations on each type of CRPA is evident for both jammer types.

V. RF FRONT END POWER & DATA RATE LIMITATIONS

While creative antenna design techniques may enable the distribution of many CRPA elements within the size constraints of the human body, power requirements must be considered for the RF front end of the system, which performs initial filtering, down conversion and amplification prior to received signals being sent to the processor. Typical man-portable navigation systems are restricted to less than 5 W of power due to battery capacity, efficiency & weight limitations.

Since both L1 and L2 frequency bands must be accommodated in many GPS systems that require anti-jam functionality, the number of RF front end component chains in the system is doubled for each antenna port within a CRPA. Total power for the RF front end of a single channel in an L1/L2 band CRPA is typically 300-500 mW. Thus, a basic four-element CRPA will likely draw a minimum of 1.2 – 2 W power for just the front end components.

With this in mind, consider the scenario in which a dual-linear polarized null-steering algorithm is employed on a four-element CRPA to mitigate the same number of jammers as a standard eight-element RHCP CRPA with half the number of array elements, in order to maximize null-steering performance on an extremely space-limited platform. The power required for the four-element dual linear polarized CRPA will remain approximately the same as the full eight-element RHCP CRPA since every antenna element in the dual linear CRPA has two output ports (vertical and horizontal polarization) and an RF front end is required each port. Thus, RF front end and processor power requirements will likely be the primary limiting factor for the number of elements capable of inclusion in a wearable anti-jam GPS antenna design.

In addition to power requirements, data rates must also be considered if the anti-jam system is to be a "plug-and-play" unit, capable of being paired with a variety of different GPS receivers without the need for full integration. As an example, if a USB 3.0 connection is employed to pair a standalone anti-jam GPS unit with a GPS receiver, the maximum transfer rate will be limited to ~640 MBps. Each RF front end analog-to-digital converter (ADC) within the CRPA will likely be between 2 and 12-bit resolution, with higher resolutions offering better dynamic range.

As shown in Table III, typical GPS data rates should be manageable by a USB 3.0 connection for a 16-channel CRPA (e.g. eight-element dual linear polarization) for 2 and 4-bit resolution but not for 8 and higher bit resolution. If the system is limited to a USB 2.0 interface between the receiver and CRPA module, with maximum transfer rate of only 60 MB/s, then a only a two-channel CRPA could be supported at 4-bit resolution and up to an eight-channel CRPA could be supported at 2-bit resolution.

TABLE III

DATA RATE (MBPS) FOR VARIED CRPA TYPE AND ADC BIT RESOLUTION

	Bit Resolution			
CRPA Type	***2-bit***	***4-bit***	***8-bit***	***12-bit***
Two-Element RHCP	25	50	100	150
Two-Element Dual LP	50	100	200	300
Four-Element RHCP	50	100	200	300
Four-Element Dual LP	100	200	400	600
Eight-Element RHCP	100	200	400	600
Eight-Element Dual LP	200	400	800	1200

VI. CONCLUSION

A variety of design consideration for a wearable anti-jam GPS antenna have been explored through simulation, measurement and analysis. Material properties of textiles may limit antenna size reduction techniques and significantly limit the number of elements of an anti-jam antenna array capable of being distributed on the human body. High dielectric constant buffer layers may be required to meet bandwidth requirements and size limitations. Employing a dual linear polarization null-steering algorithm will enable an anti-jam GPS antenna to increase its anti-jam performance with minimal sacrifice to overall RF performance and no increase in physical size. However, power requirements for the RF front end and data rate limitations of the interface to the GPS processor may be the overarching bottlenecks for man-portable anti-jam GPS systems and should be considered when the antenna and null steering algorithms are developed.

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