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(54) **METHOD AND SYSTEM FOR WAVEFORM INDEPENDENT COVERT COMMUNICATIONS**

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(57) **ABSTRACT**

A transmitted signal exploits unique higher order statistics of temporally dependent waveforms to encode message symbols with unique durations enabling low power transmission of the covert message. The message is independent of the characteristics or encoded data of the transmitted waveform. The method uses spatial fourth order cumulants or spatial second order moments in a Blind Source Separation and generalized eigenvalue decomposition to determine unique matrix pencil eigenvalues. Sequential detection in successive blocks determine the duration of the eigenvalue. The durations of the detected eigenvalues are sorted sequentially and can be sorted spatially by Steering vectors, AoA or geolocation into signal tracks that are mapped to recover the transmitted cover message. Generation of the transmitted signals with unique high order statistics may be accomplished using combination of noise generators, temporal filters, signal sources, combiners and switches. The receiver includes a multi-element array and does not need a priori knowledge of the transmitted signal source to recover the message. The methods and apparatus for covert communication does not require typical demodulation. The covert communication system is multiple access.

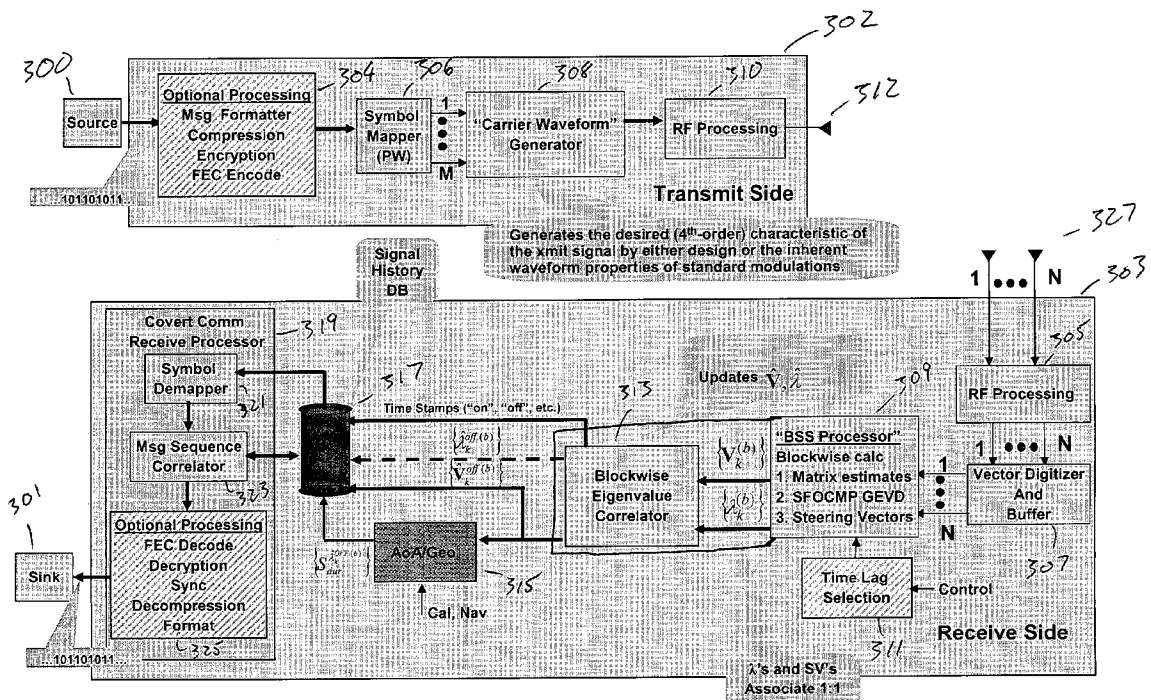


Figure 1

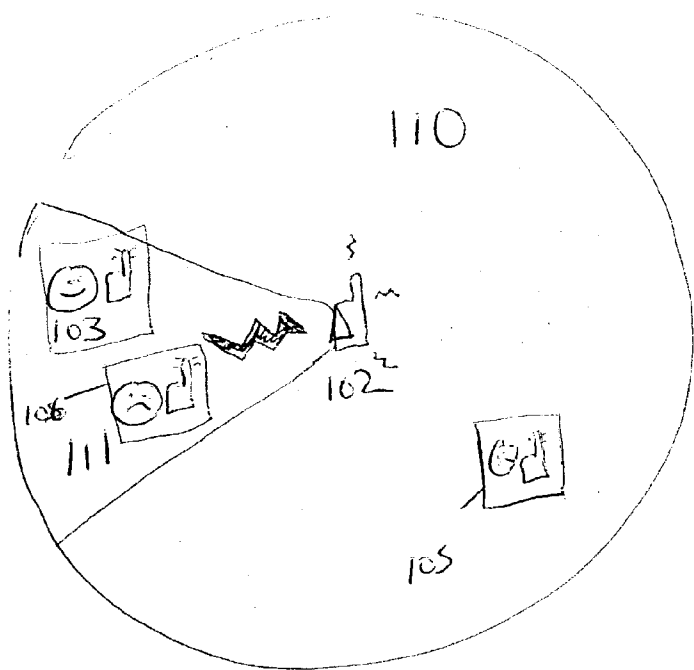


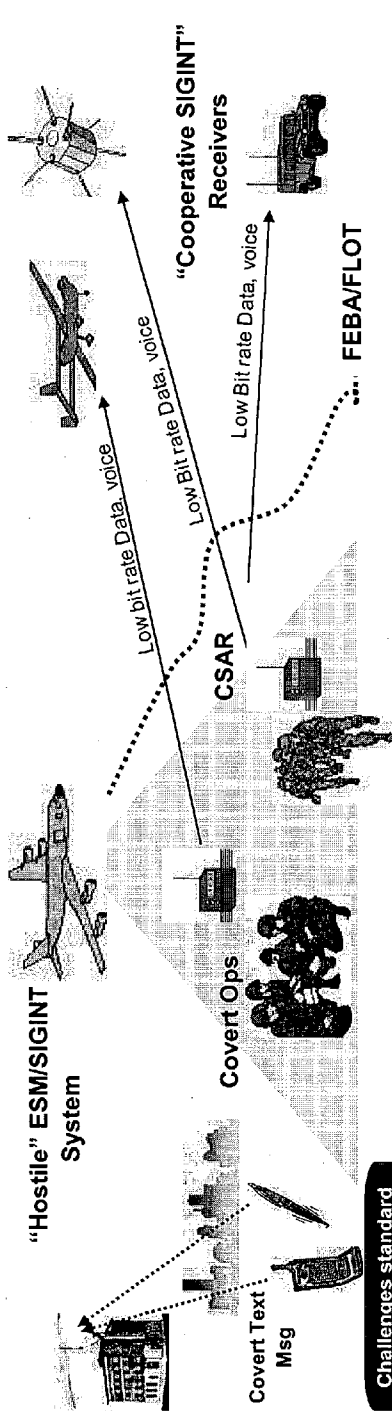
FIGURE 2

Problem: LPD/LPI Communication System with Location Capability

HARRIS

Problem

1. Covertly (LPD/LPI) communicate sensitive data (i.e. CSAR, INTEL) from a remote terminal.
2. Provide 10's - 100's Kbps rate
3. Spatially locate (AoA/geolocation) terminal transmitting message.



Features of Our Solution

- Information encoded as *matrix-pencil eigenvalue* with *M*-ary duration (from a consistent AoA).
- Low power (SNR << 0 dB) to evade energy detection and extend transmitter life.
- "Feature-less" waveform
- No code acquisition/synchronization required; no carrier/timing recovery needed
- Receiver need not know temporal domain "carrier waveform(s)"
- Scheme can be co-channel with strong ambient EM environment signals.
- Signals can be geolocated simultaneously with communication in same operation.

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Figure 3

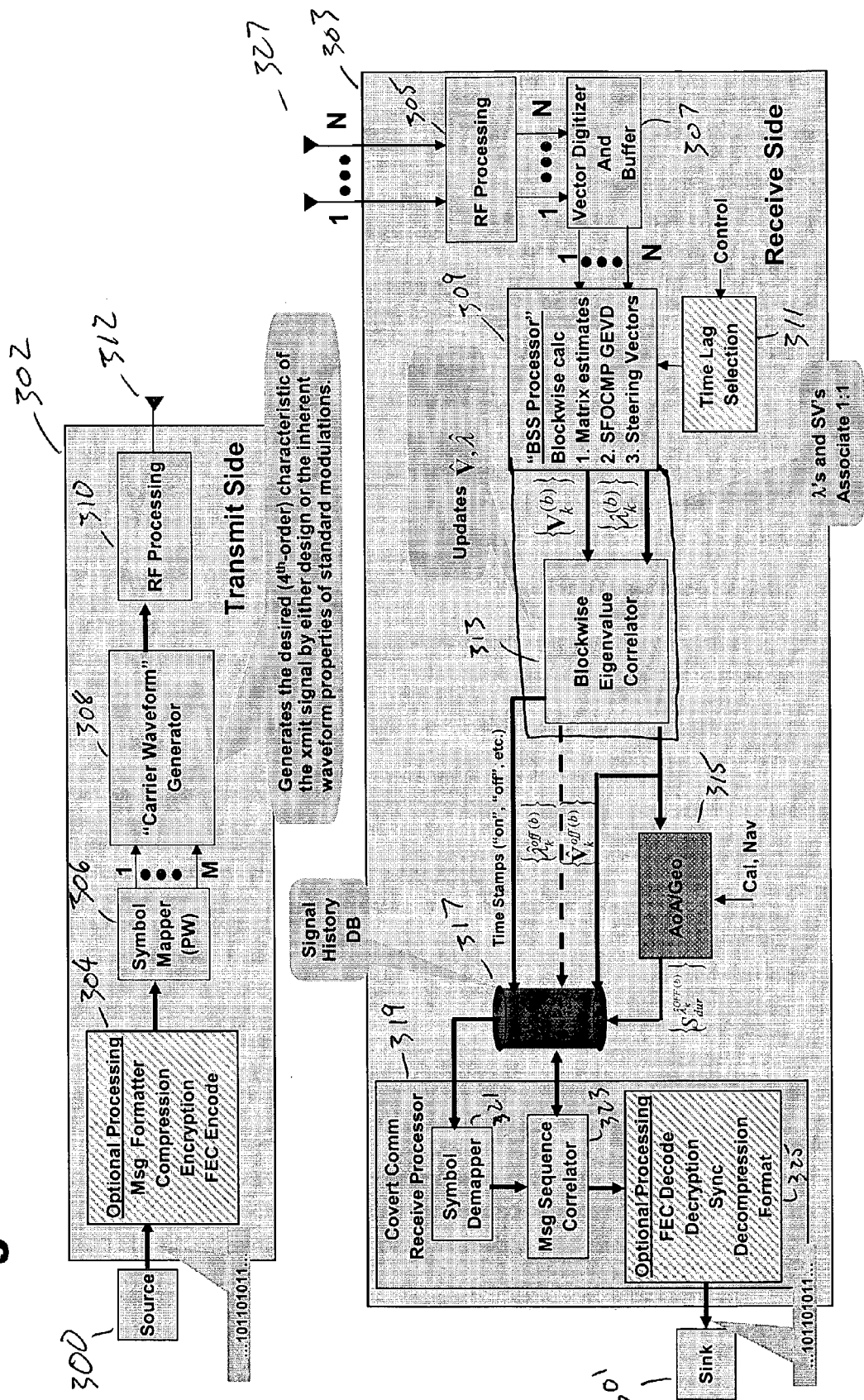
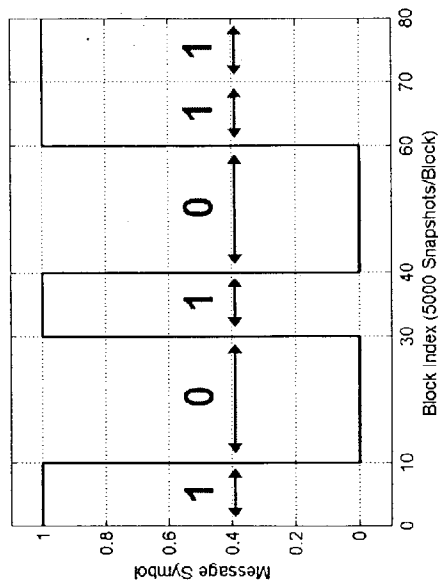


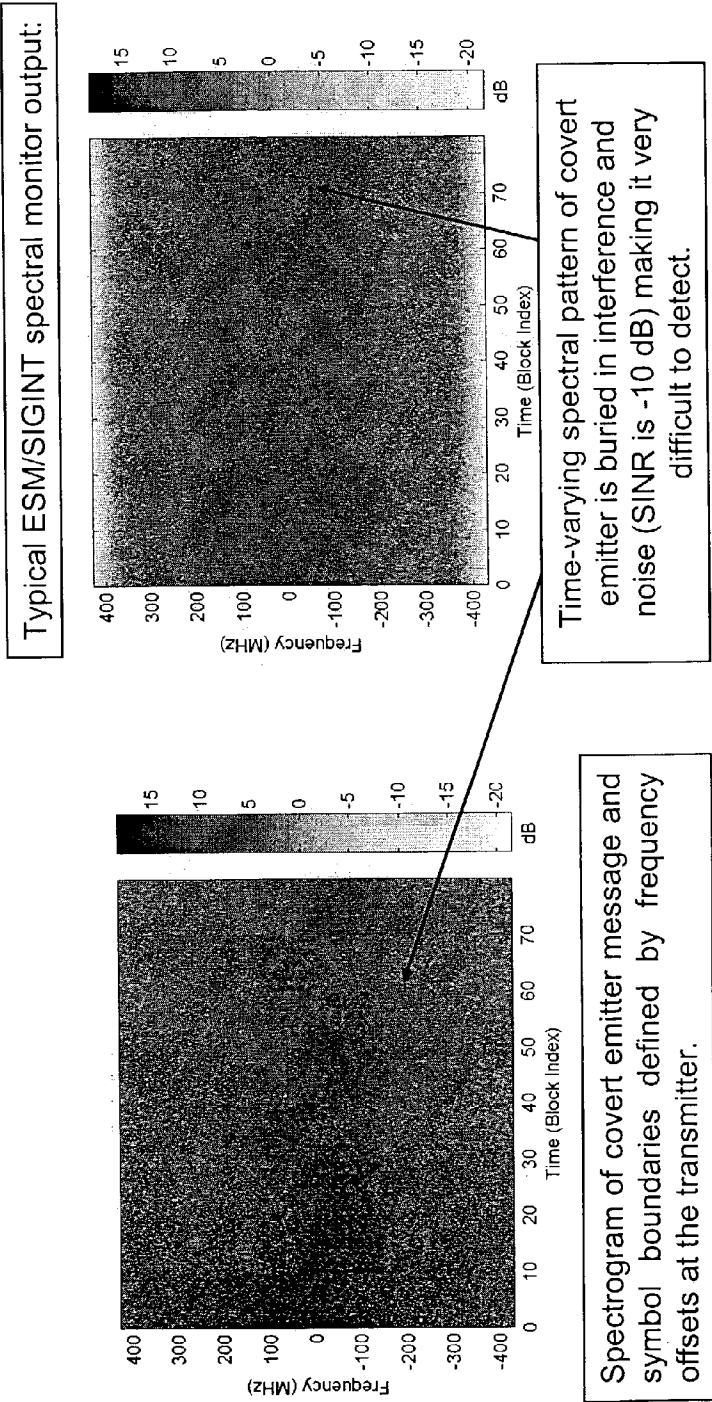
Figure 4

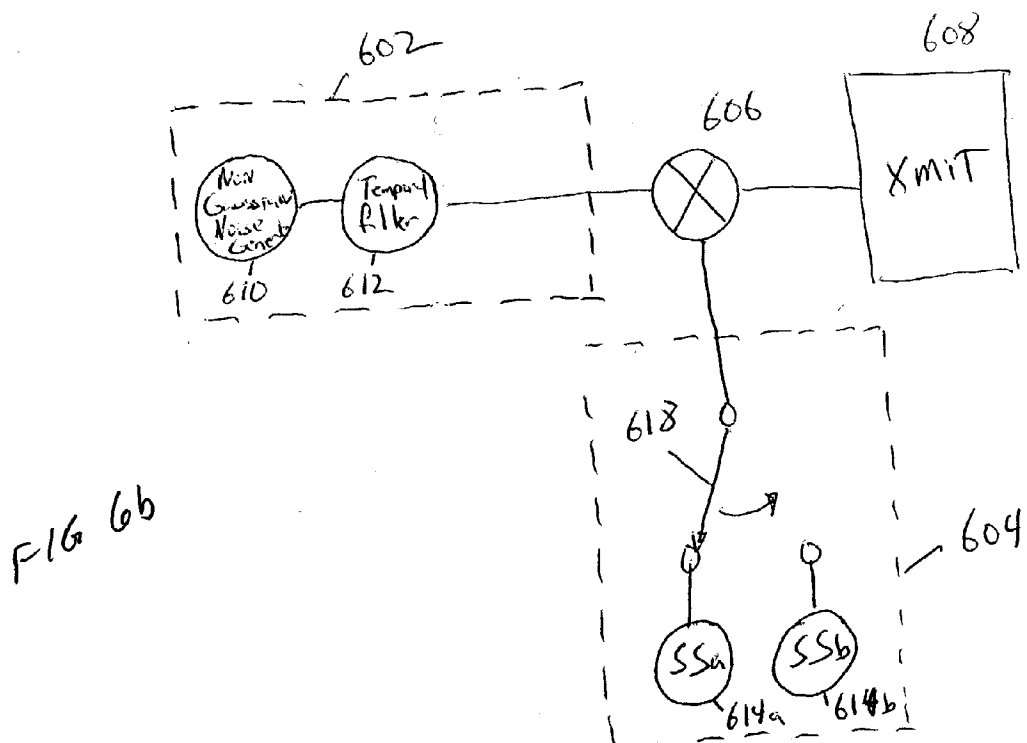
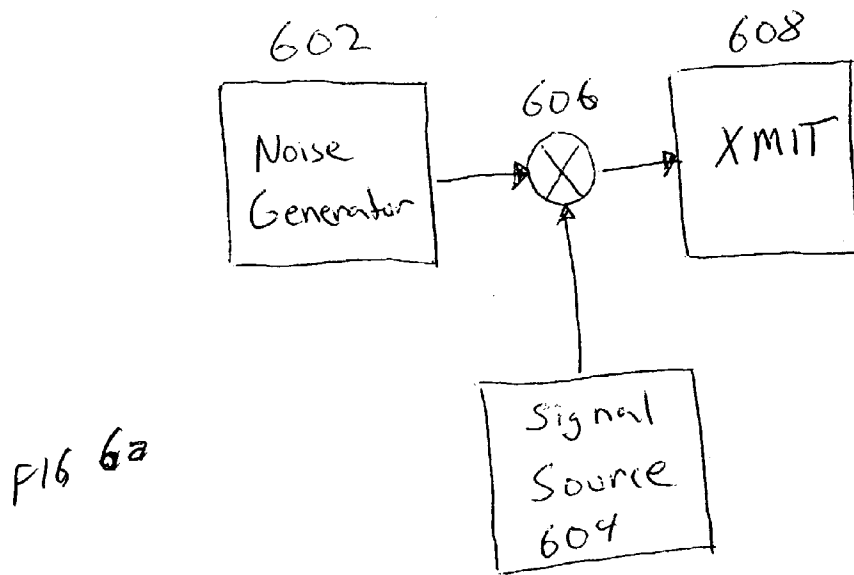


- Covert message sequence: **1 0 1 0 1 1** where symbols are:
 - 1**: 10 5k-sample blocks (50000 samples from array)
 - 0**: 20 5k-sample blocks (100000 samples from array)
- Covert baseband waveform consists of “narrowband” random noise (Laplace distribution)

Figure 52

Figure 56





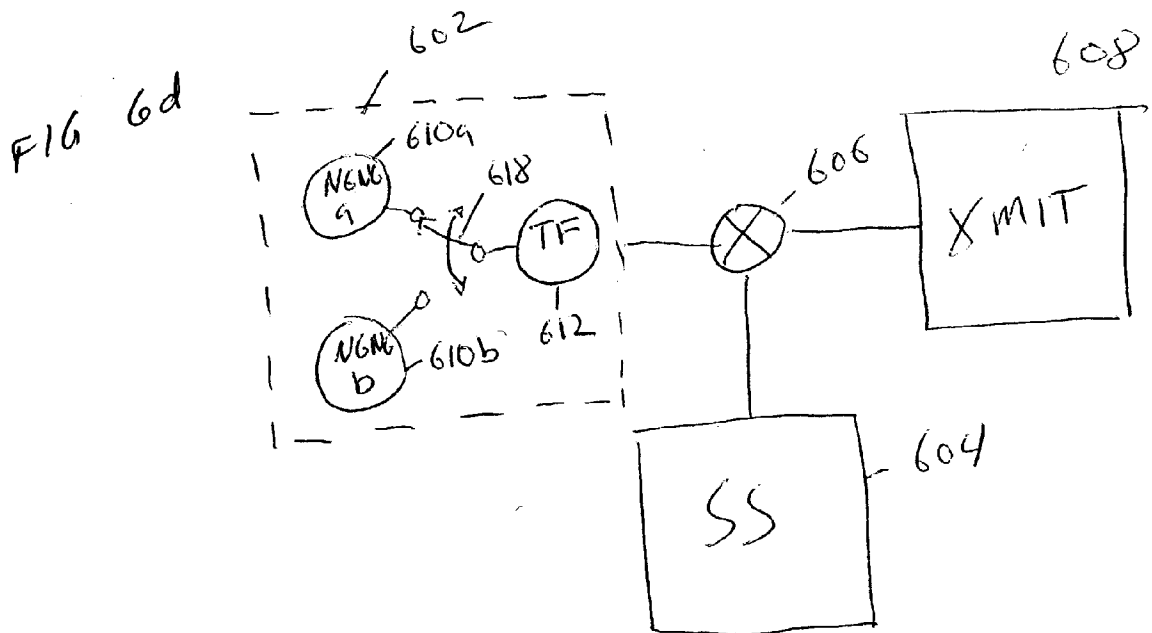
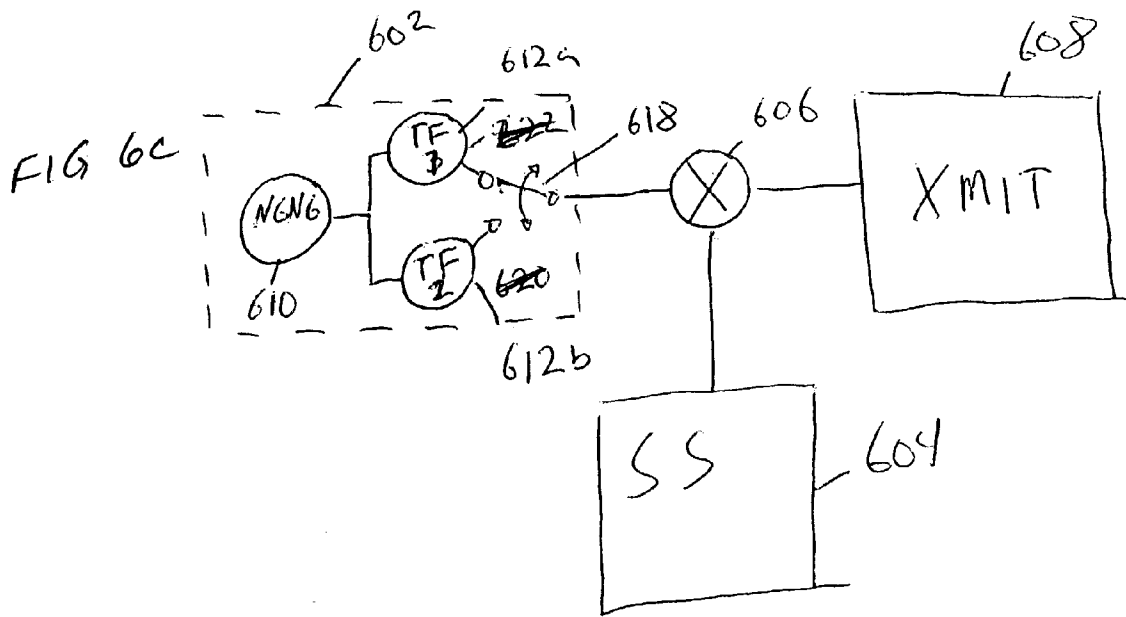


FIG 6f

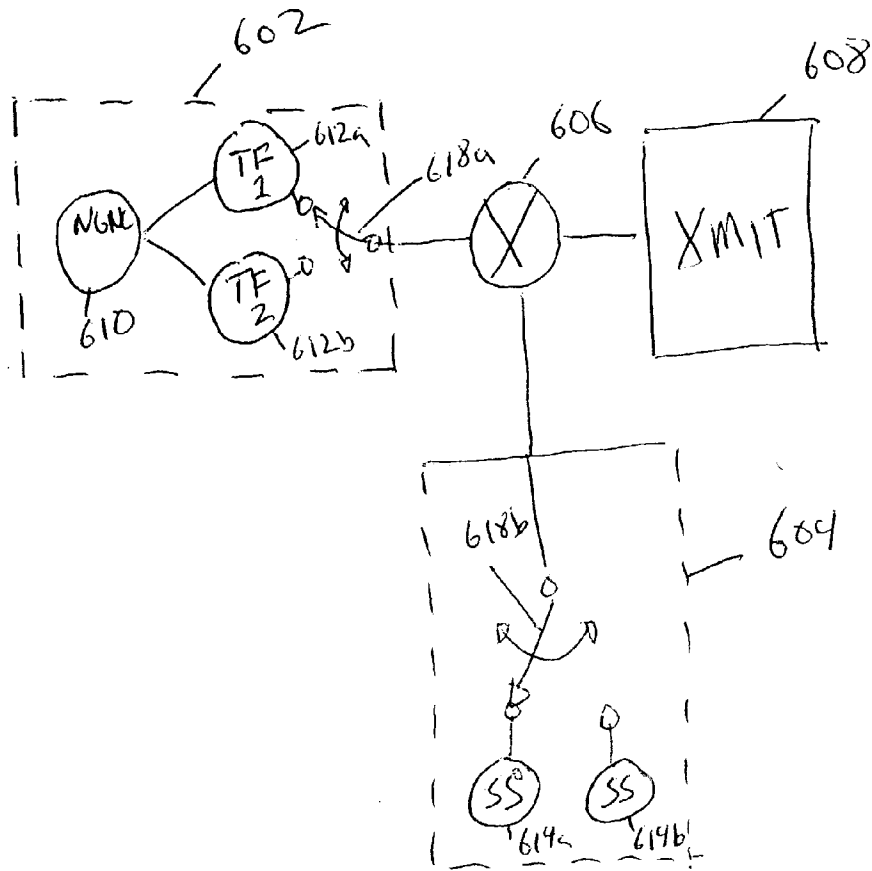


FIG 6e

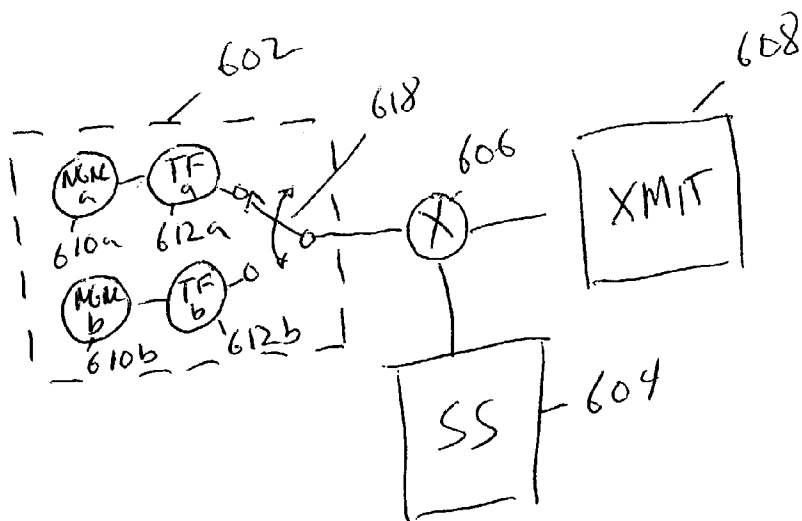
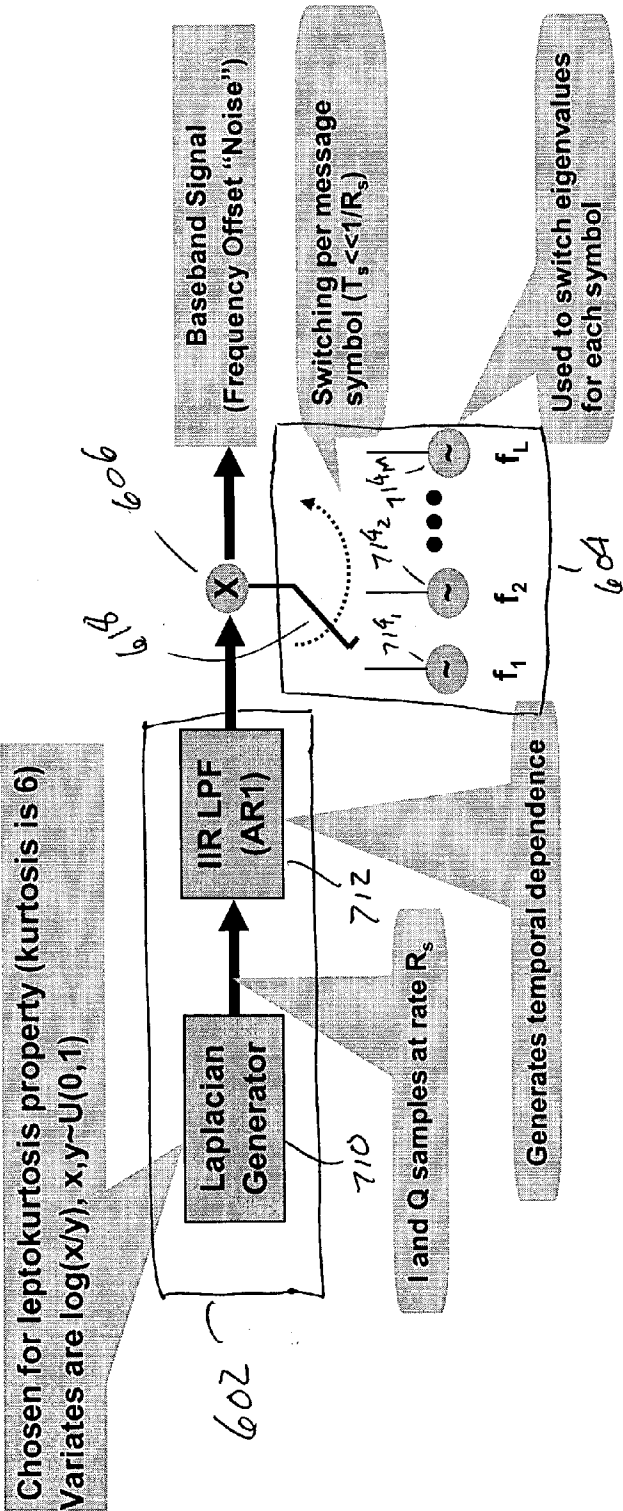


Figure 7



Notes:

- Switching can be a random or deterministic map
- Filters could be switched (i.e. max/min phase) to alter eigenvalue sequence
- Implementation could switch filters/oscillators in combinations
- Implementation could also use one or more different random sequence generators
- Instead of frequency offsets, different waveforms (i.e. BPSK/QPSK/MSK) could be used

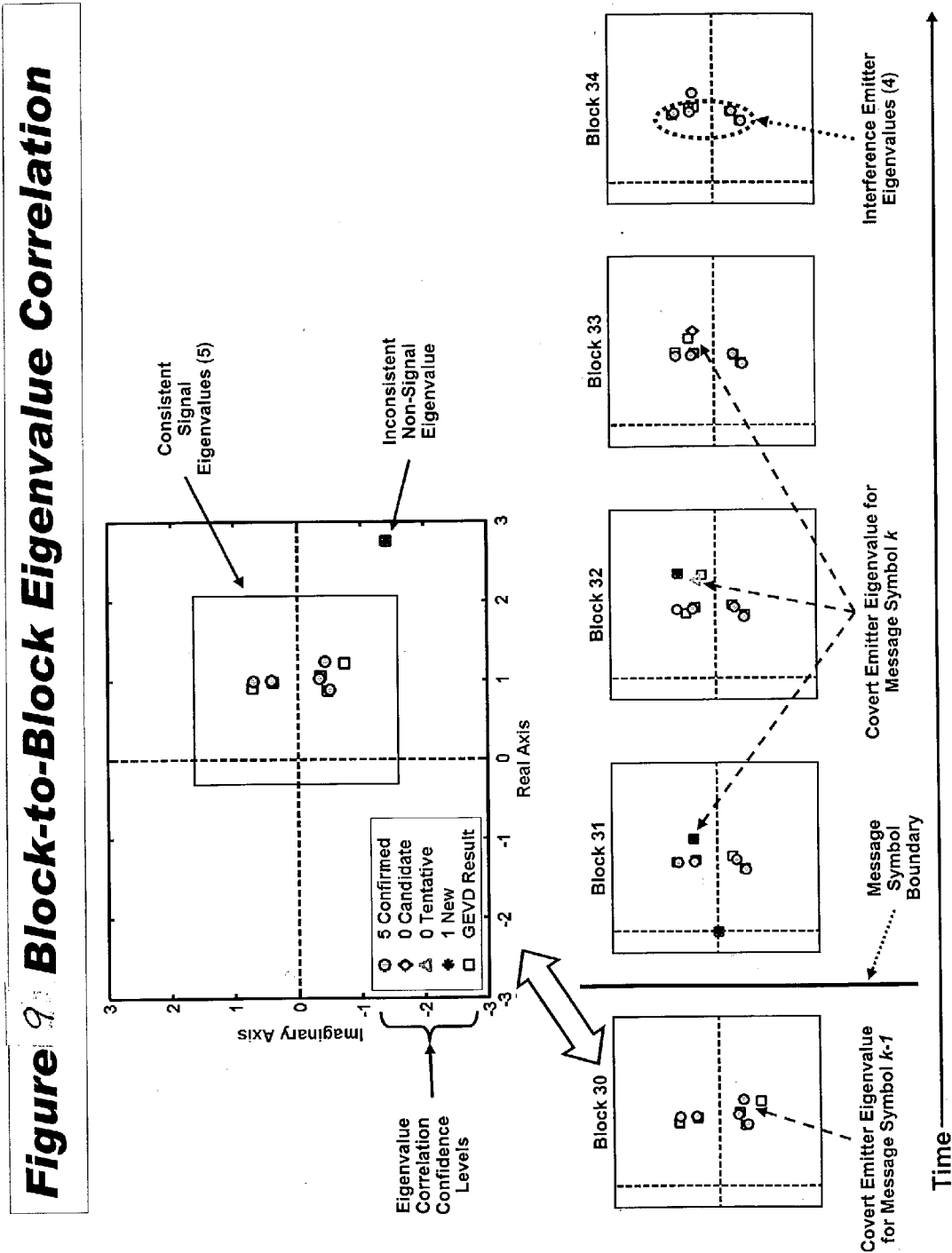


Figure 10 Spatial Information Example

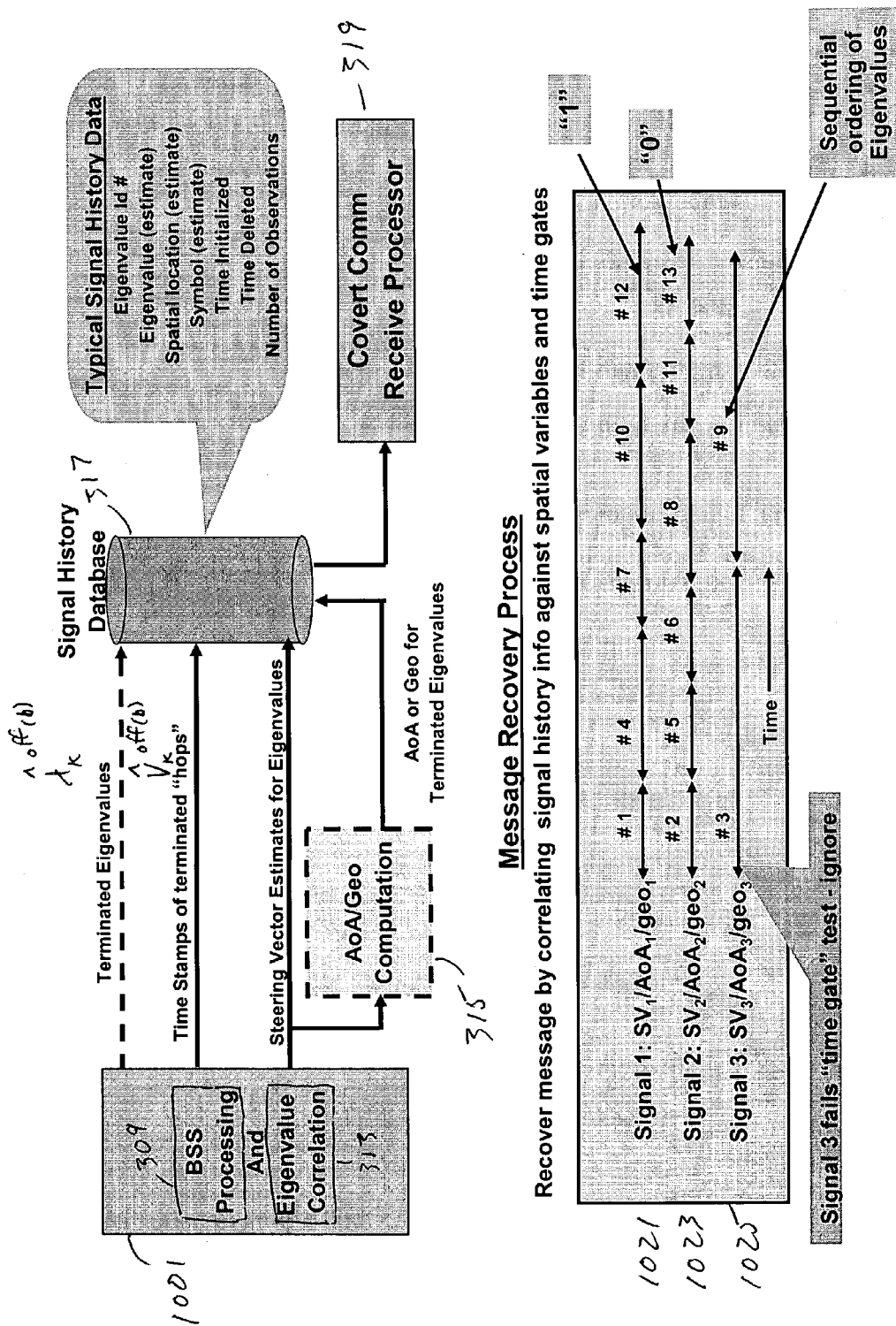


FIGURE 11

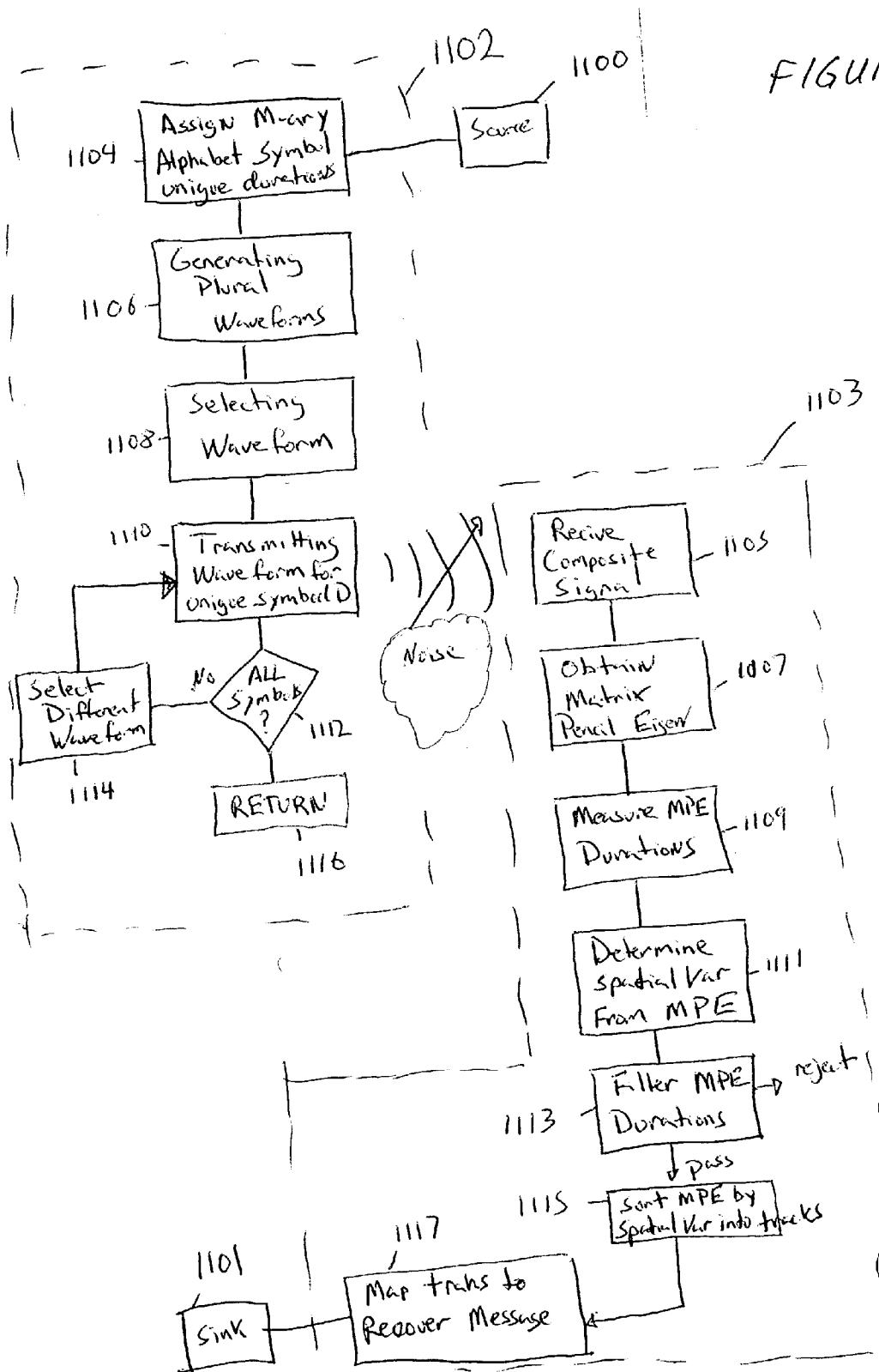


Figure 12 Without Spatial Information Example

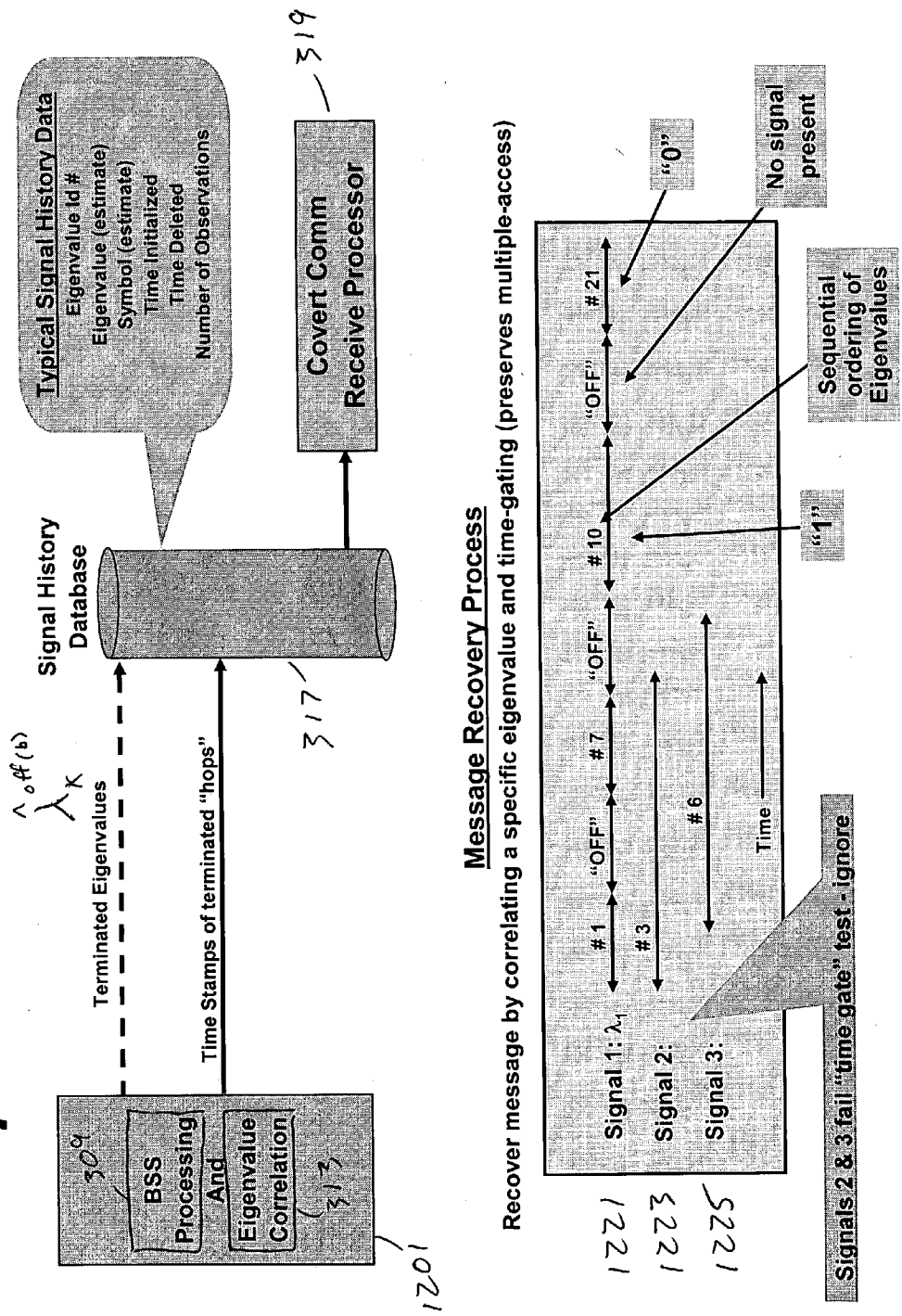
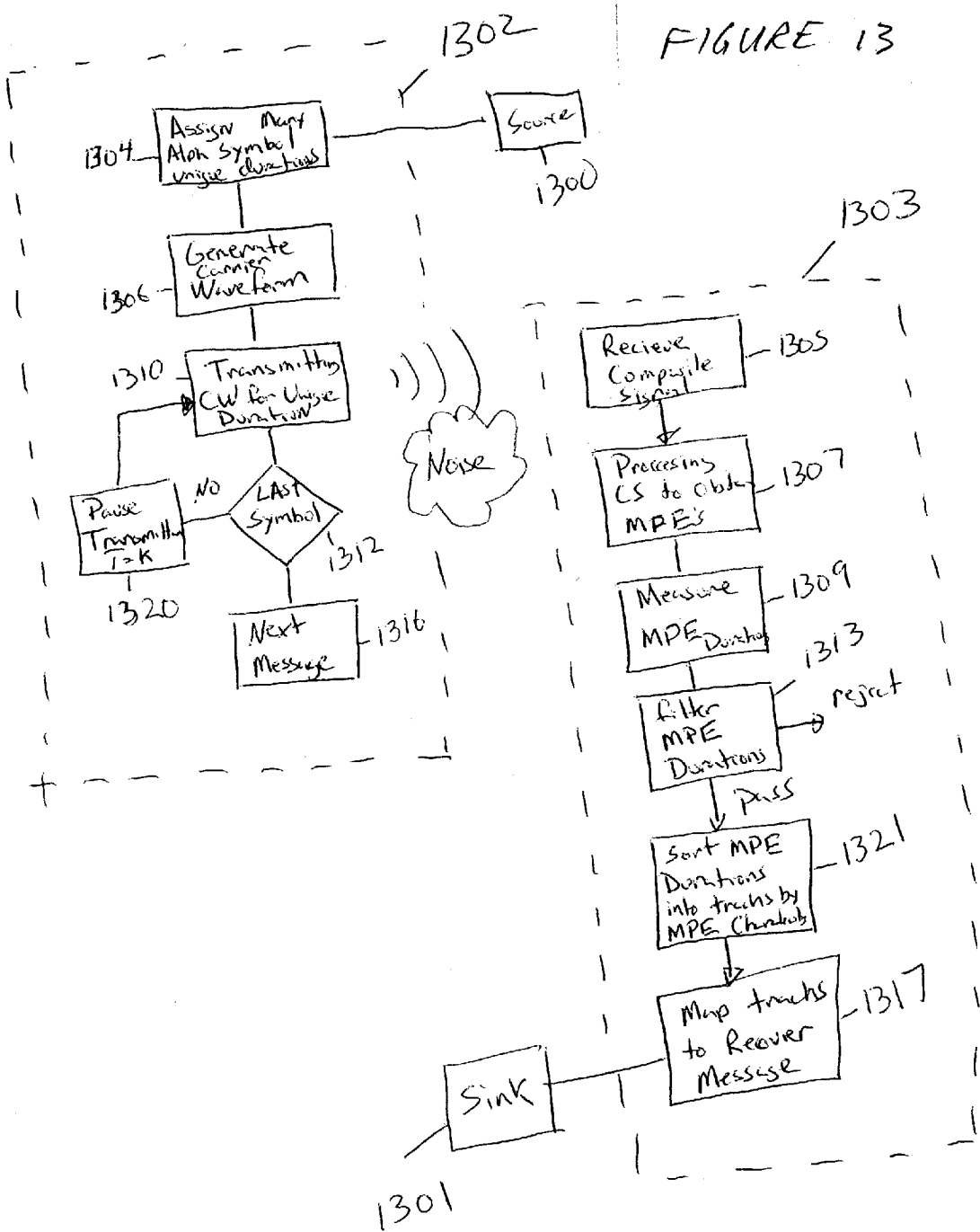


FIGURE 13



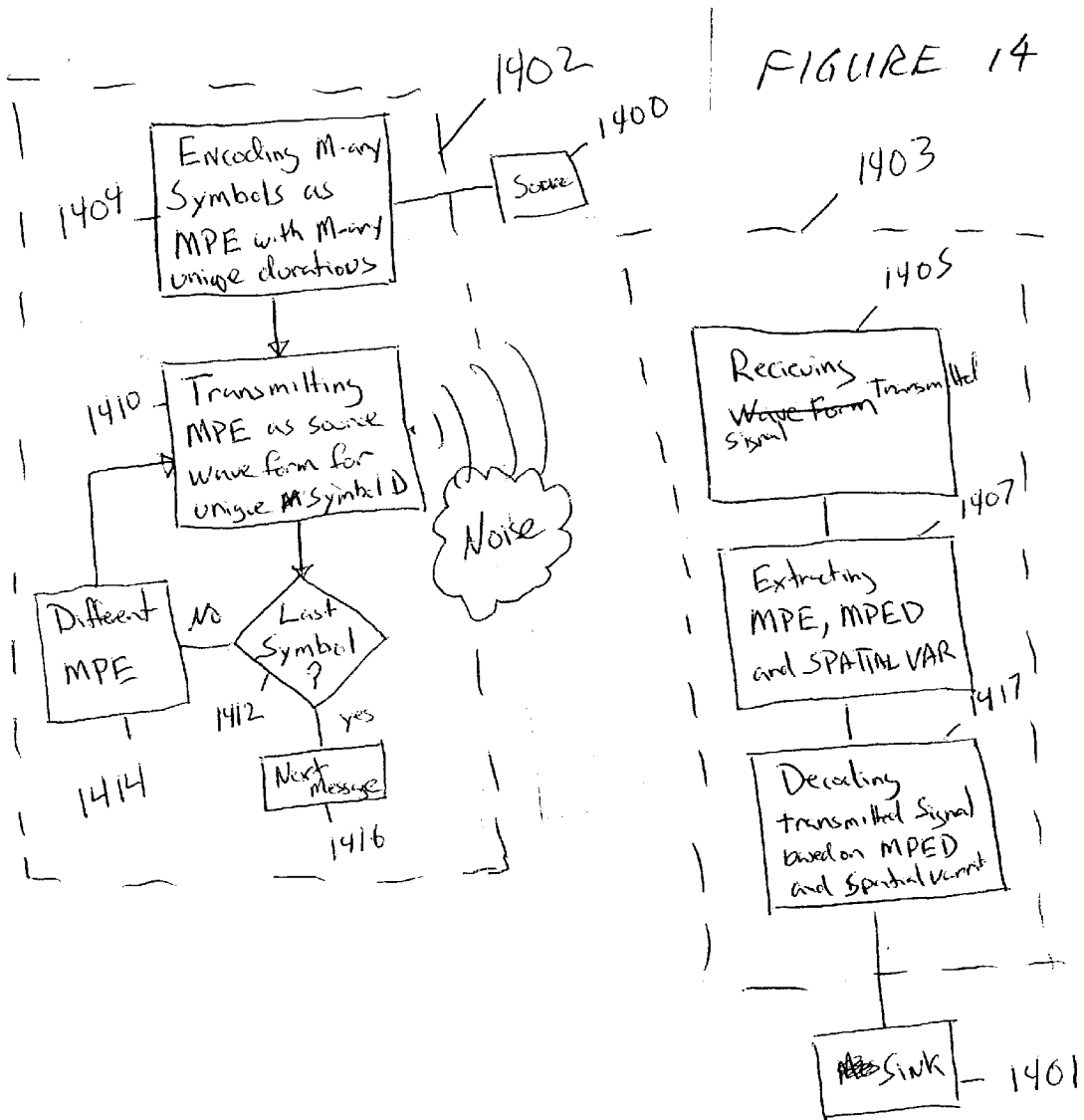
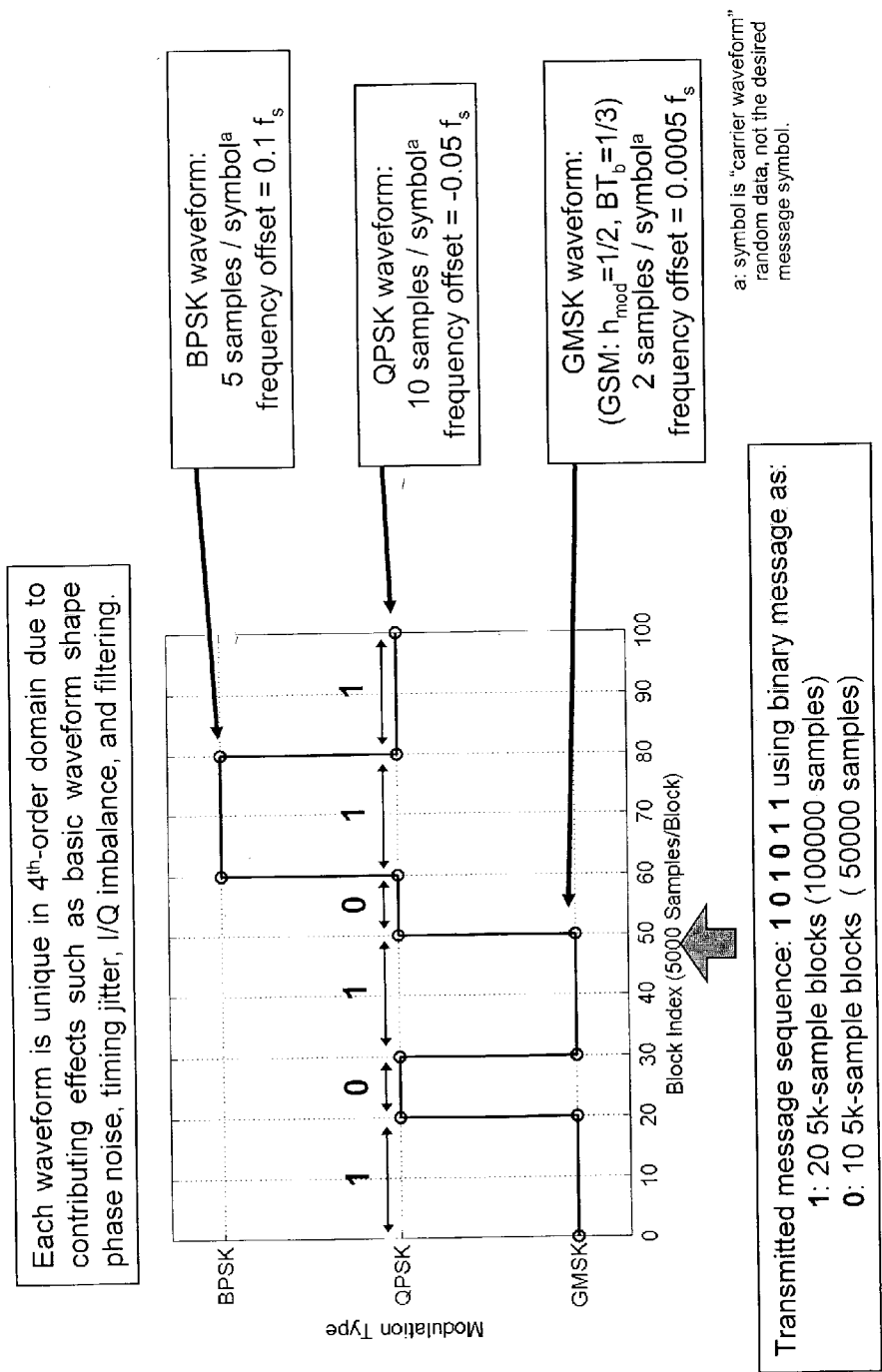


FIGURE 15



METHOD AND SYSTEM FOR WAVEFORM INDEPENDENT COVERT COMMUNICATIONS

RELATED APPLICATIONS

[0001] The present application is related to and co-pending with commonly-assigned U.S. patent application Ser. No. 10/360,631 entitled "Blind Source Separation Utilizing A Spatial Fourth Order Cumulant Matrix Pencil", filed on Feb. 10, 2003, the disclosure of which is hereby incorporated herein by reference.

[0002] The present application is related to and co-pending with U.S. Provisional Patent Application Serial No. 60/374,149 filed Apr. 22, 2002 entitled "Blind Source Separation Using A Spatial Fourth Order Cumulant Matrix Pencil", the entirety of which is hereby incorporated herein by reference.

[0003] The present application is related to and filed concurrently with U.S. Provisional Patent Application Serial No. _____ entitled "Cooperative SIGINT for Covert Communication and Location Provisional", the entirety of which is hereby incorporated herein by reference.

BACKGROUND

[0004] In the advent of globalization, information is a fundamental and valuable commodity. Information and intelligence regarding national defense and security comes at an even a higher premium. In many instances this information and intelligence can only be obtained covertly so as to not reveal the source. Information regarding location of a source such as for surveillance or combat search and rescue can be degraded in value if detected by unfriendly entities, such as enemy forces in the case of a downed pilot or a marked terrorist under surveillance. Additionally, command and control among conventional and/or special operation forces can betray missions by alerting hostile governments or organization of their presence. Embedded voice and data bugs can also expose the existence of these forces if their transmissions are detected resulting in the desired information moving out of reach of the bugging device. These are but a view of the many possible scenarios where a message is desirably sent covertly from a mobile or fixed transmitter to a remote receiver or, more importantly, a friendly or cooperative receiver with out the presence of a signal being detected by an unintended receiver. Covertly transmitting a signal may be necessary to reflect the fact that the transmission is conducted in such a way as to avoid intentional or inadvertent detection by systems monitoring the electromagnetic (EM) environment local to the covert transmitter. However, any transmission, covert or not, may be desired to be received only by intended receivers.

[0005] Intentional detection of the signal or message can be accomplished in military systems that use specially designed electronic support measures (ESM) receivers. These ESM receivers are often found in signal intelligence (SIGINT) applications. In commercial applications, devices employed by service providers (i.e. spectral monitors, error rate testers) can be used to detect intrusion on their spectral allocation. Inadvertent detection can also occur, such as when a user or service provider notices degradation in link performance (e.g., video quality, audio quality, or increased bit error rate).

[0006] The term covert also implies the additional goals of evading interception and exploitation by unintended receivers. Interception is the measurement of waveform features or parameters useful for classifying/identifying a transmitter and/or the waveform type and/or deriving information useful for denying (i.e. jamming) the communication. Exploitation is processing a signal by an unintended receiver in the attempt to locate the transmitter and/or recover the message content. In the broad literature on covert communications these characteristics as applied to transmitted information signals are referred to as low probability of detection (LPD), low probability of intercept (LPI), and/or low probability of exploitation (LPE) by an unintended receiver.

[0007] Typically an LPD communication system shown in **FIG. 1** is designed by minimizing the radiated energy in all directions. The goal is to have the emitter **102** radiate zero energy in all directions, save for the direction of the intended receiver **103**. This approach limits the geographic locations in which the signal would likely be detected. The area **110** receives little radiation and thus the unintended receiver **105** would have greater difficulty detecting the signal than the unintended receiver **106** in area **111**. Typically, LPD systems use only enough energy in the direction of the intended receiver to be reliably detected and the message recovered by the intended receiver. The radiation in non-preferred directions is primarily controlled by the aperture (i.e. antenna system) and additional performance improvement for LPD can be gained by employing a directional antenna. However, there remains a need to minimize the radiated energy necessary for the intended receiver to detect and recover the message and thus reduce the ability of an unintended receiver in area **111** to detect the signal.

[0008] Given the desirability to transmit messages covertly, it is helpful to understand considerations that enhance or degrade LPD, LPI and LPE. An unintended receiver such as the receiver **103** in **FIG. 1** with the goal of detecting a covert communication must reliably differentiate between the binary noise-only and signal-plus-noise hypothesis. As is known to those of skill in the art, for an unintended receiver the signal detection process is typically based on an energy threshold. The energy the receiver measures is given by $E_{\text{tot}} = P_{\text{avg}} T_{\text{xmit}}$. Where under general conditions the power P_{avg} is the received covert signal power S plus internal receiver noise power N . Hence, $E_{\text{tot}} = (S + N) T_{\text{xmit}}$. If the signal power used to communicate is only a small fraction of the receiver noise, $S \ll N$, it is extremely difficult for the unintended receiver to reliably detect the presence of the covert signal because the total energy detected will only be marginally greater than the noise-only ($S=0$) case.

[0009] In prior art LPD systems, the bandwidth of the message signal is artificially broadened to reduce the energy loading on the band, as is done in direct sequence spread spectrum (DSSS) communication, the intended receiver has a processing gain over the unintended receivers that use the same co-channel receiver bandwidth to capture the signal. However, for prior art DSSS, the intended receiver **103** must have knowledge of the spreading code and be able to acquire it and remain synchronized to the covert transmitter code, in addition to the usual communication receiver functions of carrier and timing recovery. This requirement, for some

applications, is not a problem but for other applications, covert message transmission functionality is greatly diminished.

[0010] Minimizing transmit power has two direct system benefits. First, the total signal power used will be a small fraction of the total noise power present in the same band. Thus, if the message is limited in time duration, the total energy measured by an unintended receiver 106, which may be an ESM receiver, is indistinguishable from a noise-only environment. Since ESM receivers are often of energy threshold type, there is an obvious trade-off of average power for time duration in order for a signal to remain undetectable. Second, the low transmit power scenario enables usage by transmitters with very limited power supplies (i.e. batteries).

[0011] Therefore, as naturally arise in military environments such as depicted in FIG. 2, there is a need for a low power message system and method, covert or otherwise, such as covert communications for Intel or Special Forces, “stealth” IFF for low observable ground vehicles, and combat search and rescue (CSAR). There is also such a need in a number of civilian or public safety applications as well, such as asset tracking/location or “lost child” detection/location and surveillance. In particular in these latter-described applications it may be particularly desirable to receive both a message and location the source of the message.

[0012] Embodiments of the present inventive system and method address the above needs while requiring only an extremely low power signal.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. 1 is a general representation of a prior art approach to LPD.

[0014] FIG. 2 depiction of covert scenarios.

[0015] FIG. 3 is a representation of an embodiment of a waveform independent covert communication system.

[0016] FIG. 4 is a depiction of a binary symbol message 101011 according to an embodiment of the invention.

[0017] FIG. 5a is a representation of a spectrogram of a transmission of the binary symbol message depicted in FIG. 4 and revealing the symbol boundaries of the message according to an embodiment of the invention.

[0018] FIG. 5b is a representation of a spectrogram of a transmission of the binary symbol message depicted in FIG. 4 as might be seen by a typical ESM/SIGINT spectral monitor.

[0019] FIG. 6a is a generalized schematic representation of embodiments of the invention.

[0020] FIG. 6b is a schematic representation of an embodiment of the invention with dual signal sources.

[0021] FIG. 6c is a schematic representation of an embodiment of the invention with dual temporal filters.

[0022] FIG. 6d is a schematic representation of an embodiment of the invention with dual non-Gaussian noise generators.

[0023] FIG. 6e is a schematic representation of an embodiment of the invention with dual non-Gaussian noise generator and temporal filter branches.

[0024] FIG. 6f is a schematic representation of an embodiment of the invention with dual temporal filters and dual signal sources.

[0025] FIG. 7 is a schematic representation of a Laplacian noise generator with multiple signal sources according to an embodiment of the invention.

[0026] FIG. 8 is a representation of eigenvalue tracks for a frequency shifter laplacian noise waveform for message “101011” according to an embodiment of the invention.

[0027] FIG. 9 is a representation of block-to-block eigenvalue correlations.

[0028] FIG. 10 is a schematic representation of a message recovery system with spatial information according to an embodiment of the invention.

[0029] FIG. 11 is a flow diagram for covert communication via message recovery with spatial information according to an embodiment of the invention.

[0030] FIG. 12 is a schematic representation of a message recovery system without spatial information according to an embodiment of the invention.

[0031] FIG. 13 is a flow diagram for covert communication via message recovery without spatial information according to an embodiment of the invention.

[0032] FIG. 14 is a flow diagram for covert communication via encoded eigenvalues according to an embodiment of the invention.

[0033] FIG. 15 is a representation of a binary message sequence 101011 encoded using different carrier waveforms.

DETAILED DESCRIPTION

[0034] A useful feature of embodiments described herein is the use of time duration to convey information, while the individual waveforms used to convey the message (in the time duration of the fourth-order characteristic) are in a sense superfluous or independent of the message to be conveyed. This is a significant advantage for ubiquitous application, allowing for parasitic use of present communication infrastructure and devices. Thus there are few restrictions on the pairing between potential covert transmitters and the intended receiver using the disclosed covert communication methods and apparatus because of the independence of the information transfer on the “carrier waveform”. This is unlike prior art systems where the receivers designed or instantiated for a certain signal type cannot accurately recover the message if the receiver is presented with another signal type. However, embodiments of the present invention by contrast can function equally well for any waveform, and the receiver does not require any a priori knowledge of the “carrier waveform”. In fact, embodiments of the covert transmitter can be waveform agile without informing the intended receiver.

[0035] The embodiments herein are predicated on selecting and transmitting carrier waveforms with unique higher order spatial statistics. Such higher order statistics include 2nd order spatial moments and 4th order spatial cumulants.

There are a number of ways that the fourth-order statistics of a high order statistic of a signal may be altered. The number of type of encoding schemes mapping an M-ary alphabet to time durations is limitless, but in point applications there will be preferred methods since they ease hardware and software realization of the system. Specific embodiments are identified herein. One method is by design, such as using frequency shifted Laplacian noise. Another method is to use the inherent properties of conventional waveforms (e.g., BPSK, QPSK, GMSK, QAM, DBPSK MFSK, FSK, and DQPSK). Yet another is to alter channel filtering in the transmitter. Common to all these approaches is that a high order statistic, specifically, but not limited to, the fourth-order characteristic, of the transmitted signal is recoverable with a spatial fourth order cumulant matrix pencil (SFO-CMP). Furthermore, the message symbols map to time durations of these higher order statistics and not to specific values of the SFOCMP. Hence, from the receiver's point of view, the communication is independent of waveform selection by the transmitter. The primary restriction is that the receiver and transmitter must use the same "codebook" of time durations and alphabet. However, the "codebook" need not be known a priori by the receiver in all instances. As shown herein, the receiver will be able to discern the different time durations and be able to extract some useful information therefrom.

[0036] To recover the message information, the waveform is not conventionally demodulated. Rather, a straightforward block or batch estimation algorithm estimates the generalized eigenvalues of the SFOCMP for each signal in the receiver field-of-view (FOV) over time using only the array output. For this discussion we assume the data has been digitized appropriately. The sizing for the block processing (e.g., the block of contiguous array observations, sometimes known as "snapshots") is dependent on several factors. Chiefly we must ensure that each block has enough sample support so that the eigenvalue estimates from the GEVD of the SFOCMP in each block over a symbol duration nominally match. This means that estimation error is negligible. Accordingly, changes in the eigenstructure can be reliably detected, and this change indicates a symbol boundary. The degree to which a nominal match is required within a block depends on the complexity of the signal environment (e.g., extraneous co-channel signals), the communication errors (e.g., partially received messages) tolerable in a given application, and the receiver processing resources to recover the message in a timely manner.

[0037] Further, in practical situations, as power sources become impaired (e.g., batteries running low on power), transmitted waveforms become increasingly distorted. This situation limits the effectiveness of matched filtering as used in prior art systems, since the concept of matched filter relies on knowledge of the transmitted waveform in the receiver. Embodiments of the inventive technique are impervious to such distortion since it is the duration and not the actual value of the eigenvalues of the SFOCMP that matter. So as long as the eigenstructure characteristic of the distorted signals is nominally constant during a message symbol, the inventive system and method is robust as to degraded transmitter performance. Therefore, the present inventive system and method will operate successfully under conditions that would normally be detrimental to conventional systems. The use of lower order matrix pencils are also contemplated by the present inventive system and method.

[0038] In FIG. 3, the source 300 produces a digital data stream of a covert message to be transmitted by the covert transmitter 302. The digital data can either be inherently digital (e.g., Morse coded messages) or analog (e.g., voice) and subsequently digitized. The digital data can also include framing or formatting of the message. Typical of the framing would be start/stop and data fields. Though other fields can be used as needs dictate. This framing structure can ensure that the receiver can reliably find the beginning of a message for synchronization. Source coding or compression could also be applied to the incoming data stream to reduce the required bandwidth. The user may also encrypt the data to protect it by an optional encryption device of suitable complexity. This data is then output to the forward error correction (FEC) module, which currently is envisioned as applying block coding. The coding is useful to aid the receiver in resolving message ambiguities say caused by fades or other unresolved time coincident measurements, which in this system could be processed as "erasures" up to the correction capability of the code. Additionally, the error correction code would find application when the symbol stream is improperly decoded due to statistical variations in the time duration measurement process. Thus, the potential for a message protocol using automated repetition of the message might be advantageous as error patterns in each transmission will likely be different. This type of protocol would require the framing as stated above, and possibly the inclusion of other fields such as the number of times the message has been or will be repeated. Message formatting, compression, encryption and/or FEC is performed by the processor 304. The processing in processor 304 is not necessary for practicing the present invention but is included to indicate the ability to add additional robustness and reliability to the transmission of a message.

[0039] The binary symbol stream is from source 300 is then mapped into suitably selected M-ary symbols (or time durations) in the symbol mapping device 306, via look-up tables or other codebook like mapping mechanisms. The alphabet size is limited only by system implementation and design considerations for particular applications. The encoded data is then applied to the "carrier waveform" by carrier waveform generator 308 which is a signal generator, implementations of which are further described below. The "carrier waveform" has its fourth-order characteristic modified according to the control by the M-ary alphabet. There is no limit to the strategies potentially adopted by the covert transmitter for this operation, so long as the characteristic is measurable reliably by the receiver and it conforms to the time duration and alphabet size assumed by the receiver. To this end, there will be some minimum duration and maximum duration for a symbol, and a preferred duration increment for each symbol in the alphabet. The exact choices depend on application, however, making the durations too disparate can negatively affect data rate limiting this technique to lower data rate applications. It is desirable to provide durations that are easy to resolve into the M-ary symbols. The baseband data from the carrier waveform generator 308 is fed to a suitable RF subsystem 310 and antenna 312 for transmission.

[0040] The minimum duration and duration increment must be such that synchronizing the data block boundaries used in the receiver to that of the symbol timing in the transmitter 302 is not relied upon. It is desirable that the covert transmitter 302 use a fundamental signaling period of

several (e.g., 10) "receiver block" durations for the minimum signal, and may have a signaling duration increment of the same size to define the alphabet. However other choices are applicable depending on the particular implementation and application. The goal is to make the time duration alphabet as disparate as possible while meeting performance objectives (e.g., data throughput). Sample data rate computations can be determined as shown below.

[0041] Defining S as the array snapshots/block, "b" blocks for the minimum length symbol, "B" blocks for the maximum length symbol, and "R" as ADC (analog to digital converter) conversion rate in the receiver, the minimum and maximum symbol durations for a binary alphabet are:

$$T_{\text{sym}}(\text{min}) = S * b * 1/R = 5,000 * 10 * 10^{-9} = 50 \times 10^{-6} \text{ sec}$$

$$T_{\text{sym}}(\text{max}) = S * B * 1/R = 5,000 * 20 * 10^{-9} = 100 \times 10^{-6} \text{ sec}$$

[0042] The values b=10 and B=20 along with S=5,000 and R=1 Gsamples/sec are subject to implementation choice, and used here for illustration only. Assuming that a system would have an equal number of binary symbols of each type, the average (over the long-term) data rate is nominally 13 kbps. If M-ary signaling is implemented with the same maximum and minimum symbol durations, the data rate can be improved by factor of $\log_2(M)$, but at potentially increased channel BER. Achievable data rates are in principle limited by operating conditions (received SNR, tolerable BER, cumulant estimation errors, etc.). In addition to reliably detecting a change in the SFOCMP eigenvalues using a basic correlation technique, a minimum b consecutive blocks are required (currently b=4) for each of S vector samples from the receive array, thereby making the theoretical minimum symbol duration equal to bS(1/R). Similarly, the incremental time duration for the alphabet should be at least ES(1/R), where E is the number of blocks desired by the designer to provide a balance between adequate safety margin in the time duration decision process and required throughput rate. In theory, E can be as low as unity which would enhance the achievable signaling rate for a fixed alphabet size. However, this is likely not a practical choice since numerous errors can occur due to the receive block processing not being time aligned to transmitter symbol boundaries. Conversely, selecting a large value for E for a fixed alphabet minimizes the effect of block misalignment, but limits the available data throughput. In the present binary example E=10 thereby yielding symbol durations of 10 blocks and 20 blocks for the binary alphabet. For M-ary alphabets, one might construct an alphabet with uniformly spaced symbol durations yielding durations of (b+qE)S(1/R) where q=0, 1, 2, 3, ..., M-1. An alphabet of equally-spaced symbol durations might be selected for convenience of implementation, but non-uniform spacing of the symbol durations is not precluded by the teachings of the present invention. It shall be understood by those of skill in the art that the values given above are exemplary only and are not to be construed as limiting the invention in any way.

[0043] The receiver 303 uses an N-element (or port) receive array 327 and an RF processor 305 to obtain the transmitted signal. In order to capture the temporal character (i.e. the time duration modulation of the SFOCMP eigenvalues) of the covert signal, the array data is first sampled and digitized at some rate suitable for the application. Each array output is digitized simultaneously producing a vector observation in the vector digitizer and buffer 307. The array

output data is buffered and subdivided into non-overlapping blocks in 307. Block-wise across signal samples (i.e. the vector observations) are then collected from an array at the intended receiver aperture and the cumulants are block estimated, the matrix pencil is formed, and the generalized eigenvalue decomposition (GEVD) is performed by the Blind Source Separation processor 309. The operation of the BSS requires the selection of a triplicate of time lags provided by the time lags selection device 311. The GEVD provides a set of N eigenvalues $\lambda_k^{(b)}$ and N eigenvectors $V_k^{(b)}$, where k=1, 2, 3, ..., N (i.e. assuming an N-port array is used) for each block of data. The superscript b is used as a block counter in the receiver. We assume there are M_s generalized eigenvalues representing the SFOCMP properties for each of the M_s signals in the field of view (FOV) of the receive array 327, $M \leq N$. The remaining N- M_s eigenvalues are of the indeterminate (i.e. 0/0 type). Thus when using a sequence of block estimates for the SFOCMP eigenvalues of the M_s consistent signals will be apparent. Further processing is required and performed in the communication receive processor 319 to assemble valid messages. A major part of this processing is to use spatial information available from the GEVD processing. The spatial information regarding the transmitter location and the message content are linked in a 1:1 fashion by the generalized eigenvalues produced by the processing in 309. Using the "side information" of the available spatial variable greatly eases message recovery since we assume that a transmitter spatial location will be "slowly" varying (i.e., changing at a rate much less than the symbol rate of the message), hence a message can be reconstructed in part by looking for message symbols represented by eigenvalues and their durations, associated with a "consistent" location. The designer must ensure that the symbol duration alphabet has sufficient minimum support and increments such that the practical time duration recovery issues where ambiguous results can be obtained do not adversely affect the system performance.

[0044] As may be apparent to those of skill in the art, there may be some advantage to overlapping blocks of the data. However, the following discussion deals with non-overlapping blocks. On each block, the two fourth-order spatial cumulant matrices required to form the SFOCMP are formed using pre-selected delay triplets. The delays can be either pre-selected, or subjected to online modification using a programmed search routine (if necessary). This search routine might be necessary when certain conditions, such as repeated eigenvalues for different signals are encountered. Processing of the received covert message this difficulty is likely of no consequence. However, provisions are made for signals whose eigenstructure match at the delays selected to be repressed at different delays to provide improved discrimination if desirable. After the matrix pencil is formed, the GEVD is computed. From the GEVD, the eigenvalues and eigenvectors are used to determine the signal environment over time block b. Subsequently, the eigenvectors are used to determine the signal steering vectors and then the eigenstructure is correlated block wise in the Blockwise Eigenvalue Correlator 313 to determine any changes in the signal environment. A change, such as symbol boundary, in the communication signal will alter its contribution to the signal environment eigenstructure, measured by the SFOCMP, in a detectable manner. This means a "significant" movement in the complex plane of eigenvalues. As signal

changes are detected, those signals are cued for storage in the signal history database 317. As part of the storage procedure, the spatial location of the signal is determined (i.e., either angle-of-arrival (AOA) or geolocation, whichever applies given the specific application) by the AOA/Geolocation processor 315. Additionally, the steering vector can be recorded, which is useful when refined spatial information is unavailable and the relative motion of the transmitter and receiver is negligible. The eigenvalues no longer correlating with the present signal structure are also written to the database. The temporal support (i.e. durations) of the eigenvalues no longer correlating with the current signal structure is measured and stored. All this data is formed and recorded in the signal history database 317 along with other ancillary data that may be useful for signal post-processing applications such as data mining or covert message recovery.

[0045] An important function of a tracker is the track initiation and deletion logic. An embodiment of the tracks uses a fixed distance and a fixed number of consecutive “good associations” for initiation and a single “no association” for a track deletion. A “good association” is any measurement that is “close enough” to track. A “no association” condition occurs when all the measurements are “Too far” from a particular track. the distance indicative of an good association can be set empirically or experimentally. Track initiation and track deletion strategies can also be used to adapt to various situation. A Kalman-like approach to association gates can be adapted as the number of observation for a track are accumulated. Such an approach also has the advantage of replacing fixed averaging of the measurements.

[0046] To recover the covert message, in the covert communication receive processor 319, first the time durations are time-gated and those passing the time-gate are then mapped to the M-ary symbols of the “codebook” by the Symbol Demapper 321. The Message Sequence Correlator 323 is an association engine that “stitches” all the signal eigenvalues durations and symbol values corresponding to a “consistent” spatial location into a time-ordered stream or signal track. After the data is assembled into streams, the data is supplied to the optional data processor 325, where the data can then be FEC decoded, decrypted (if necessary), decompressed (if necessary) and then the message can be checked for synchronization, as well as, the data provided to the sink 301 with the appropriate format.

[0047] The design also allows for multiple access for communications. Consider the case where multiple remote covert emitters are sending data. It is unlikely that they would have exactly the same fourth-order cumulant representation, even if they are using the same base waveform. This is because any deviation from nominal waveform implementation (e.g., frequency change, waveform change, matrix pencil eigenvalue change, phase noise, I/Q imbalance, timing jitter, phase jitter, symbol rate change, pulse shape change, a fourth-order statistic change, relative rotational alignment of a signal constellation change, power amplifier rise/fall time change, and Doppler shift change) causes the fourth-order statistics of these signals to differ. Further, the multiple access signals are assumed distinguishable by spatial location. Of course this requires enough data to be collected to resolve the location, and the array must also provide such resolving power. But, if automated location is not possible at the receiver, due to, for instance, no

calibration, the covert transmitters may still have multiple access if the multiple access signals can be assured uniqueness amongst themselves and the environment of sufficient degree in the SFOCMP eigenvalues. The receiver need not know the exact eigenvalues that will be used, but in this mode it is incumbent on the individual transmitters to use one and only one eigenvalue and not switch waveforms. In principle, correlation algorithms to properly sort this data are readily imaginable, though the details depend specifically on the signal designs. And of course if location of the covert emitter is still is necessary, the remote covert emitter could encode his position, say from his GPS, into the data stream. This might make the encryption more important, and certainly elevates the need for LPD/LPI capability.

[0048] Returning to the concept of the SFOCMP, it is not correct to think of the possible eigenvalues for a given transmission to constitute a signaling constellation. While signaling using the eigenvalues could be approached this way, it is not a requirement. This would restrict the choices and implementation and performance for the system. The full flexibility of the proposed approach is reached when we allow a non-constant mapping of the baseband symbols (i.e. time durations) to the potential plurality “carrier waveform” options available in the transmitter. The number of “carrier waveforms” can exceed the M-ary alphabet. For example, some alternative “carrier waveforms” might be encountered as distortions of the canonical set such as when power systems or components degrade over time or for some reason the system designer desires a larger signal set be available.

[0049] A specific example of waveform design to be feature-less is shown in FIG. 4 and FIGS. 5a and 5b. FIG. 4 is a representation of a binary message sequence 101011 where the symbols are discriminated by duration. In the transmitter the binary sequence is mapped to binary time durations. It shall be readily appreciated by those of skill in the art that the process may be extended to M-ary time durations. In response to a new symbol, the carrier frequency for the embodiment shown is offset at the time boundaries, thus shifting the fourth-order cumulant (i.e., the eigenvalue) for that symbol. Ultimately the time duration of the eigenvalue is recovered to reconstruct the message. The frequency shift for the repeated “1” symbol at the end of is needed (in this case) to differentiate a repeated “1” from a single “0” and visa versa in the case of a double “0” (not shown). In particular the temporal correlation of the SFOCMP eigenstructure must be broken at a message symbol boundary. This break of temporal correlation in FIG. 5a is accomplished by altering the fourth-order cumulant with a frequency shift.

[0050] FIG. 5a is a spectrogram of the emitter message shown in FIG. 4 when using the frequency shifts of the preferred embodiment discussed herein. The symbol boundaries defined by frequency offsets at the transmitter are clearly evident in the spectrogram. FIG. 5b is a representation of a typical Electronic Support Measures (ESM) receiver/Signal Intelligence Spectral Monitor output viewing the received signal of FIG. 5a. With reference to the spectrogram shown in FIG. 5b, the time varying spectral pattern of the message shown in 5a is buried in interference and noise (SNIR<-10 db) making the covert message very difficult to detect, and thus even more difficult to intercept

and exploit. As is known to those of skill in the art the acronym SNIR stands for Signal to Noise and Interference Ratio.

[0051] Given an environment with several interferers and the already negative received SNR an unintended receiver (even using a front-end filter) will likely not reliably detect the presence of the covert signal. But even if a machine detects the presence of the signal energy, it would likely not be acted upon since it would fail all modulation recognition tests and show no exploitable temporal structure. The signal represented in FIG. 4b is frequency shifted Laplacian (double-exponential) Noise. Viewed by a casual observer the signal would mimic additional thermal noise, hence even if detected by an energy detector of suitable design, the detection would likely be discarded.

[0052] A mathematical element of the invention is the use of spatial high order statistics to separate signal sources, such as a blind source separation algorithm that utilizes a normalized spatial fourth-order cumulant matrix pencil and its generalized eigenvalue decomposition (GEVD). The equations presented herein use the following subscripting convention. Quantities relating to the array observations available to the system are denoted with a boldface subscript \mathbf{x} . However, the subscript should not be confused with the representation of the vector observation from the array output, also denoted as a boldface \mathbf{x} . From the context the meanings shall be clear to those of skill in the art. Further, quantities relating to the propagating signals impinging on a receive array are denoted with a boldface subscript \mathbf{r} . Following this convention, the matrix pencil of the array output data is given as is given as equation 1. An assumption is made that the received signals \mathbf{r} comprising the vector observation of the array output \mathbf{x} are independent. Therefore the spatial fourth-order cumulant matrix pencil (SFOCMP) of the array output $\mathbf{P}_{\mathbf{x}}$ can be written as:

$$P_{\mathbf{x}}(\lambda, \tau) = C_{\mathbf{x}}^4(0, 0, 0) - \lambda C_{\mathbf{x}}^4(\tau_1, \tau_2, \tau_3) \quad (1)$$

[0053] where the arguments of the pencil $\mathbf{P}_{\mathbf{x}}$ represent a generalized eigenvalue, λ , and a triplet of time delays, τ . The theoretical set of finite generalized eigenvalues turns out to be the inverse of the normalized fourth-order autocumulants of the M signals,

$$\{r_i(t)\}_{i=1}^M$$

[0054] in the field of view (FOV) during the observation interval. The terms $C_{\mathbf{x}}^4$ represent the spatial fourth-order autocumulant matrices. The arguments of the terms indicate the triplet of time delays used to form the matrices. The explicit computation is given as

$$[C_{\mathbf{x}}^4(\tau_1, \tau_2, \tau_3)]_{rc} = \sum_{i=1}^N \text{Cum}[x_i^*(t - \tau_1), x_i(t - \tau_2), x_r(t), x_c^*(t - \tau_3)]$$

[0055] where the matrix is $N \times N$, and the subscript rc indicates the element in the r^{th} row and the c^{th} column. The

subscript on the function \mathbf{x} in the argument on the right-hand side, indicates which array port, $i, r, c=1, 2, \dots, N$, is being used.

[0056] Because of the unique definition of the pencil of the array output data $\mathbf{P}_{\mathbf{x}}$ is related to the pencil of the impinging signals $\mathbf{P}_{\mathbf{r}}$ as given in equation 2

$$\begin{aligned} P_{\mathbf{x}}(\lambda, \tau) &= C_{\mathbf{x}}^4(0, 0, 0) - \lambda C_{\mathbf{x}}^4(\tau_1, \tau_2, \tau_3) \\ &= V[C_{\mathbf{r}}^4(0, 0, 0) - \lambda C_{\mathbf{r}}^4(\tau_1, \tau_2, \tau_3)]V^H \\ &= VP_{\mathbf{r}}(\lambda, \tau)V^H \end{aligned} \quad (2)$$

[0057] The quantity V shown in equation 2 is a $N \times M_s$ matrix composed of the steering vectors for each signal impinging on the array, where N is the number of array ports available to the user and M_s , $M_s \leq N$, is the number of signals. In a very simplistic and idealized case the well-known array propagation vector is a steering vector (i.e., the time delay is represented as phase). However, in general if the array is well-designed (i.e., no grating lobes) and the signals are emitted from non-identical locations, then the matrix V is of full rank. This guarantees an equivalence between the eigen structure of the pencils $\mathbf{P}_{\mathbf{r}}$ and $\mathbf{P}_{\mathbf{x}}$.

[0058] Since $\mathbf{P}_{\mathbf{r}}$ is a pencil solely of the received signals, and the signals are assumed independent, then by virtue of the properties of cumulants, the pencil $\mathbf{P}_{\mathbf{r}}$ is diagonal. This property does not hold true for the pencil formed with the array output data \mathbf{x} . However, because of "equivalence" finite eigenvalues of $\mathbf{P}_{\mathbf{x}}$ are the finite eigenvalues of $\mathbf{P}_{\mathbf{r}}$, access to an exploitable high-order statistical property the eigenstructure of the SFOCMP is available. As introduced here these eigenvalues represent the fourth-order characteristics of each received signal. Specifically, each signal in

$$\{r_i(t)\}_{i=1}^M$$

[0059] contributes one finite eigenvalue, and it is expressed as the inverse normalized fourth-order autocumulant for that signal as expressed by equation 3.

$$\lambda_m = \frac{C_{r_m}^4(0, 0, 0)}{C_{r_m}^4(\tau_1, \tau_2, \tau_3)} \quad \text{for } m = 1, 2, \dots, M \quad (3)$$

[0060] where the terms

$$C_{r_m}^4$$

[0061] represent the individual fourth-order cumulant terms for each signal. These terms are actually the diagonal terms of the pencil $\mathbf{P}_{\mathbf{r}}$ as shown in equation (4).

$$P_r(\lambda, \tau) = \begin{bmatrix} c_{r1}^4(0,0,0) - \lambda c_{r1}^4(\tau_1, \tau_2, \tau_3) & 0 & \dots & \dots & 0 \\ 0 & \ddots & & & \vdots \\ \vdots & & c_{rj}^4(0,0,0) - \lambda c_{rj}^4(\tau_1, \tau_2, \tau_3) & & \\ \vdots & & & \ddots & \vdots \\ 0 & \dots & \dots & \dots & c_{rM}^4(0,0,0) - \lambda c_{rM}^4(\tau_1, \tau_2, \tau_3) \end{bmatrix} \quad (4)$$

[0062] Thus the GEVD of the two pencils P_x and P_r have the same set of finite solutions for the eigenvalues. The eigenvalues are the terms where the rank of the pencil is reduced. It should be readily apparent that values given by equation (3) are the eigenvalues of the pencil equation (1).

[0063] These eigenvalues are available to an analysis system, and in theory are independent of system Gaussian noise level given sufficient length data records. The eigenvalues are implicit characteristics of the signals carrying the emitter's covert message in each symbol duration. To exploit this property, as mentioned before, the receiver will typically form blocks or batches of received data for the purpose of correlating the eigenstructure over time to determine patterns of persistent values (FIG. 3) augmented by the availability of spatial data. It is important to recall that only the time duration of the emitter's statistical characteristic as measured by the SFOCMP is relevant, and not the exact values. Hence, the emitter is completely free to choose the "carrier waveforms" at will (FIGS. 6a-f).

[0064] The steering vectors can be estimated from the cumulant data for each signal in the FOV of the receiver. A cumulant matrix formed by the receive data, say $C_x^4(0,0,0)$ and for each eigenvector available from the pencil P_x forms,

$$C_x^4(0,0,0)e_x^{(i)} = \left[\sum_{i=1}^M c_{r1}^4(0,0,0)v_i v_i^H \right] e_x^{(i)} = \beta v_i$$

[0065] The last equality follows directly from the fact that each eigenvector of the SFOCMP P_x is orthogonal to each signals steering vector, $v_i^H e_x^{(i)} = 0$ when $i \neq j$. This fact is generated by the unique construction of the SFOCMP and the definitions of the cumulants.

[0066] In FIG. 3, the Blind Source Separation processor 309 forms and applies a separation Matrix and enumerates the number of sources. As described above, from an array output the spatial 4th order cumulant matrices are estimated and the estimates are used to determine the eigen analysis for the first-order matrix pencil. Signal detection and enumeration providing the number of source is performed and the separation matrix from the pencil eigenvectors is accomplish. The separation matrix is also used to determine spatial variables, such as steering vectors, AoA or geolocation in block 315 of FIG. 3.

[0067] There are numerous ways the covert transmitter can control the desired characteristic of its emitted waveform, some of which leave lower-order statistics unchanged. For example altering the channel filter (i.e. Nyquist pulse shaping) between maximum phase and minimum phase

realizations is undetectable in the second-order domain (i.e. power spectra), but evident in the fourth-order domain as measured by our SFOCMP. Also one could conceive on signaling with kurtosis, a fourth-order statistic, applied in the transmitter. Or, one could simply shift between classic waveforms, for example, BPSK, GMSK, QPSK, QAM, or potentially even just variants (i.e. constellation rotations, different pulse shape filters) of a fixed modulation type. There also exists the possibility that the "carrier waveforms" might be chosen as chaotic to appear more noise-like or designed using numerical techniques and generated using direct synthesis in a transmitter.

[0068] In any scheme adopted, the information transfer from the transmitter to the receiver is contained in the duration of the change in the eigenvalues of the SFOCMP, not the particular eigenvalues. Since our technique is independent of the particular eigenvalue, it is independent of the waveforms used by the emitter. Which allows, in principle, any transmitter to make use of the receiver having the capability to exploit fourth-order cumulants. The degree to which a specific emitter wishes to "hide" from say conventional ESM receivers holds the implications on the implementation details of the "carrier waveforms".

[0069] FIG. 6a is a generalized schematic diagram of an embodiment of a noise signal generator for a waveform independent covert communication system. A noise generator 602 generates temporal dependent non-Gaussian noise. The output of the noise generator 602 is combined by combiner 606 with a carrier signal or waveform source 604. The combiner can be an adder, a mixer, a multiplier, a non-linear device or other type of combiner that facilitate a change in a higher order signal statistic. This list of combiners is not exhaustive and should not be construed to limit the scope of the invention. The combined signal forms a type of baseband signal that is processed (eg. amplified, upconverted, etc.) and transmitted by transmitter 608. The generalized elements in FIG. 6a form a basic framework and facilitates several different embodiment for noise signal generation and transmission of a covert message. The generalized diagram in 6a as well as embodiment shown in FIGS. 6a-6e presented to illustrate variations of noise signal generators and not intended to limit the scope of the disclosure.

[0070] FIG. 6b is a specific implementation of FIG. 6a with dual signal sources. The noise generator 602 is implemented with a Non-Gaussian Noise Generator (NGNG) 610 and a temporal filter 612 that creates an output with temporal dependence. The signal source 604 is implemented with two unique signal sources 614a and 614b. Unique signal sources

614a and **614b** are selected to create unique spatial high order statistics when combined by the combiner **606** with the output of the noise generator **602**. The unique signal sources **614a** and **614b** are connected to the combiner by a switch **618**. The switch is driven by the symbol bit stream of the covert message. The switch **618** connects alternate unique signal sources at the conclusion of each successive symbol duration. It is important to recall that only the time duration of the emitter's statistical characteristic as measured by the SFOCMP is relevant, and not the exact values. Therefore the emitter is completely free to choose the carrier waveforms. While two unique signal sources are shown in **FIG. 6b**, multiple unique signal source can likewise be applied with the switch alternating between the signal sources.

[0071] **FIG. 6c** is another specific implementation of **FIG. 6a** having dual temporal filters. The noise generator **602** is implemented with a non-Gaussian noise generator **610** connected to two unique temporal filters **612a** and **612b**. The unique temporal filters **612a** and **612b** are selected to create unique spatial high order statistics of the transmitted combined signal (e.g. maximum and minimum phase filters). The unique temporal filters **612a** and **612b** are connected by switch **618** to the combiner **606** and combined with the output of the signal source **604**. Again the switch is driven by the symbol bit stream of the covert message in the same manner described above for the dual signal source implementation. The signal or waveform transmitted from transmitter **608** of **FIG. 6c** provides alternating unique spatial high order statistics for each successive message symbol independent of the symbol transmitter.

[0072] **FIG. 6d** is a specific implementation of the noise generator **602** including two unique non Gaussian noise generators **610a** and **610b** connected by switch **618** to the temporal filter **612**. Again the output of the noise generator combined with the signal source **604** in combiner **606** and transmitted by emitter or transmitter **608**. The unique NGNGs **610a** and **610b** are likewise selected for their effect on spatial high order statistic of the transmitter signal.

[0073] **FIG. 6e** is an implementation similar to the noise generator **602** of **FIG. 6d**, where a non-Gaussian noise generator **610a** and temporal filter **612a** form a unique branch and NGNG **610b** and temporal filter **612b** form another unique branch. The branches are unique in the sense of their respective spatial-high order statistics. The branches are connected to the combiner **606** by switch **618**.

[0074] Combinations of the specific implementation described and others that should be readily apparent from an understanding of this disclosure are likewise envisioned. **FIG. 6f** is but one of the many possible combinations. The implementation of the noise generator **602** of **FIG. 6d** containing two unique NGNGs **610a** and **610b** coupled with the signal source **604** of **FIG. 6b** containing two unique signal sources **614a** and **614b**. While the switches **618a** and **618b** are constrained to switching at only at the duration boundaries, their operation advantageously would operate independently. The result of this specific implementation allows for switching between four unique signals.

[0075] **FIG. 7** is an embodiment using a Laplacian generator **710** and an infinite impulse response low pass filter **712** (e.g. an autoregressive single-pole filter) as the noise generator **602**. The Laplacian generator **710** is chosen for

leptokurtosis property. We have chosen to form the necessary sequence of random Laplacian variates by selecting a pair of random variates, say x and y , uniformly distributed between 0 and 1 and forming $\log(x/y)$ for each sample required. For complex baseband symbols a total of four uniformly distributed variates must be sampled providing a stream of complex samples where the real and imaginary parts of each are independently Laplacian distributed. The output of the noise generator **602** is combined by combiner **606** with the signal source **604**. The signal source **604** is implemented with multiple unique signal sources **714₁**, **714₂**, . . . **714_L** that are used to switch spatial high order statistics (i.e. matrix pencil eigenvalues for the present embodiment) for each symbol of the covert messages. The unique signal sources **714** shown are offset in frequency to provide unique matrix pencil eigenvalues. In this particular embodiment, L must be greater than or equal to the alphabet size M .

[0076] As shall be understood by those of skill in the art, the specific example discussed above may be extended to use random mappings of frequency offsets over time. Also, we could alter the channel filter. There is no requirement that the filter be IIR as shown in the Figure. A number of alternative implementations could be chosen depending on the application. The key feature of the filter is to introduce a temporal dependence of the input noise waveform. Further one could also consider altering the input noise generator. However, a consideration is to select a source with suitable fourth-order properties. Any or all of these parameters can be modified to control the fourth-order properties for the transmitted waveform so long as the "codebook" constraints (time duration and alphabet size) are maintained. A natural alternative to frequency shifting, would be to pulse the carrier on/off. However, this approach reduces the number of signal samples available for geolocation given a fixed observation interval as discussed hereafter.

[0077] If one wished to use standard waveforms as the "carrier waveforms" this mode of operation is also possible with this invention. The transmitter shown in **FIG. 7** could be modified to look like alternatives shown in **FIGS. 6b-6f**. It is also important to notice that any deviations from a nominal waveform type, such as a QPSK waveform without phase noise or timing or I/Q imbalance, will cause a detectable shift in a signal's fourth-order statistic. In principle, the basic waveform need not be altered from QPSK to say BPSK, but uniqueness can be achieved by controlling the parameters of, for example, timing jitter, "carrier waveform" symbol rate, phase noise, pulse shaping and the like to provide the necessary separation in the fourth-order domain or other high order domains. The "carrier waveforms" can contain completely worthless symbols, hence anyone trying to conventionally exploit the "carrier waveform" information would be wasting their time, alternatively the "carrier waveforms" may carry information with a secondary message. However, a secondary message contained within the carrier waveform would not necessarily be LPE, LPI or LPD.

[0078] An example of a potential message recovery embodiment is shown in **FIG. 8**. To recover a message the receiver requires three parameters relative to the time durations of the message symbols. The receiver must know the minimum symbol duration **801**, maximum symbol duration **803**, and some other information regarding the other $M-2$

symbols in the alphabet. In the embodiment shown in **FIG. 8** only a binary symbol alphabet is used. This information can be provided, say by policy where the symbol duration increments are integer-related to the minimum symbol duration **801**. In this case the receiver need only know the maximum duration, the minimum duration and alphabet sizes. Otherwise the receiver can just know a-priori the pre-selected durations which can then be arbitrarily selected. The symbol durations should be selected in an application for easing the decision process in the receiver to map the measured durations to one of the alphabet elements. In this case we used a symbol twice as long as another, but such widely disparate time durations may impact throughput. A minimum symbol duration threshold **807** and a maximum symbol duration threshold **811** can be used as a time gate to remove spurious or interfering tracks. Spatially correlated signal tracks **823**, **825**, **827** and **829** are examples of eigenvalue durations which exceed the threshold in the time gate and thus are ignored or discarded.

[**0079**] Spatially correlated eigenvalue time durations **805₉**, **805₁₆**, **805₃₆**, **805₅₃**, **805₆₈** and **805₈₀** are sequenced in signal track **821**. The eigenvalue time duration of signal track **821** are compared to a decision threshold **809** to map and recover the encoded message "101011" of signal track **821**. Where a M-ary alphabet is used M-1 decision thresholds are required.

[**0080**] An illustration of a portion of the block-to-block eigenvalue correlation result is shown in **FIG. 9**. For block **30** of the covert emitter example in **FIG. 4**, the large complex plane diagram in the top portion of the **FIG. 9** shows the complex eigenvalue locations of the SFOCMP (GEVD) results and the predicted locations of the blockwise eigenvalue correlator. The legend identifies the four levels of eigenvalue correlation confidence, ("New," "Tentative," "Candidate," and "Confirmed"). The five consistent signal eigenvalues of the four co channel interferers and of the covert emitter are indicated by the smaller rectangle. The inconsistent non-signal eigenvalue outside this box tends to move about the complex plane in an erratic/unstable fashion from one block to the next. In this block **30** of this example, the covert emitter eigenvalue lies below the imaginary axis. Blocks **30** and **31** correspond to two different symbols. The lower portion of **FIG. 9** illustrates the blockwise changes in eigenvalue locations over blocks **30** to **34** where the message symbol "boundary" occurs between blocks **30** and **31**. For blocks **31** to **34**, the covert emitter eigenvalue lies in a consistent location above the imaginary axis of the complex plane. The stronger co channel interference source eigenvalues, within the oval for block **34**, lie in consistent locations over all five blocks. In a case involving pulsed interference emitters, the consistency of the spatial locations of the interference emitters and covert emitter allow message recovery embodiment to "stitch" together eigenvalues that fall within a "time-gate" and come from the same spatial location.

[**0081**] As mentioned above, using a simple time-gating operation in the receiver, it is possible to determine which eigenvalues are potentially information carrying. By correlating the GEVD over many blocks of data the persistence of the eigenvalues can be measured. The persistence of eigenvalues of the SFOCMP over time from the covert transmitter provides the signaling mechanism. However, there may be a number of extraneous pulsed signals in the

FOV time coincident with the desired communication signal. This makes message recovery complicated, though with proper message construction and error recovery/correction (i.e. FEC), the system is robust to several types of errors such as "erasures" when ambiguous results may be obtained in the decoding and symbol recovery errors. These results can be encountered due to signal fades (i.e. erasures) or symbol recovery errors in the receiver due to statistical fluctuations in time duration measurements exceeding a tolerable threshold. We can correct improper decisions regarding the detection of a symbol in the message in the receiver using typical error control coding.

[**0082**] An embodiment of the receiver **303** is shown in **FIG. 10**. The receiver **303** augments the message recovery process by using spatial information regarding the locations of the transmitters in the field of view. In **FIG. 10** signal detections are performed in processor **1001** which is composed of a BSS processor **309** and (eigenvalue) tracking processor **313** previously described. The results of the blockwise processing and eigenvalue correlation previously described are stored in the Signal History Database **317**. The data envisioned for the database are signal characteristics measured which include but are not limited to eigenvalue identification number, time initialized, time deleted, number of observations, an estimate of the eigenvalue, and importantly an estimate of the spatial location associated with the eigenvalue. To recover the message in the communication receive processor **319**, it is advantageous to initially time gate (filter) all the detections (i.e. durations of the eigenvalues) to limit the scope of the message recovery process. The detections surviving the time gate test are stored in the signal history database **317** along with other associated eigenvalue characteristics, including but not limited to Signal track identification, Symbol estimate, Time initialized, time deleted, number of observations and importantly spatial location. The detections are assembled into strings of symbols (tracks) using the criteria that a message must associate with a "consistent" spatial location. The preferred spatial information is angle-of-arrival (AoA) or geolocation for each signal detected in each block which are determined in the AoA/Geo computation processor **315**. This requires that the receiver platform have knowledge of the N-port sensor array calibration and the platform position during receipt of the covert message, such knowledge would normally be available. For simplicity of presentation, from hereon the term "spatial location" or spatial variable refers to AoA if only calibration is known, or geolocation if both receiver position and array calibration are known. It is preferable that the spatial relationship between the transmitter **302** and receive array **327** be fixed over the message length, however, a slowly varying spatial property can be accommodated by introducing a method to correlate a sequence of spatial variables across contiguous blocks of data in the receiver **303** specifically in the Message Sequence Correlator **323** of the Covert Communication Processor **319**.

[**0083**] Spatial correlation can be broadened to include simply steering vectors. This is useful when the array and transmitter have a stable geometry. Relative motion between the transmitter and sensing array causes the steering vectors to have a detrimental time dependency. Again, if the spatial variable for correlating the message data is "slowly" varying then small incremental changes can be tolerated. The covert messages is indented to be recovered using a "consistency" of the spatial domain information of the computed eigen-

structure from the SFOCMP for the signals of interest. But to account for the possibility of “fixed” location emitters and other emitter who are not of interest to the communication process, a time-gate decision process as noted earlier is advantageously applied. This way the receiver need only attempt to decode “message strings” that emanate from “consistent” spatial locations with the appropriate time character.

[0084] Although access to the spatial variables using only the receive array output data has been previously described. It is useful to note a blind source separation algorithm based on a fourth-order cumulant matrix pencil produces eigenvectors that are orthogonal all but one signal’s steering vector. Thus using the eigenvectors it is possible to estimate each corresponding signal’s steering vector. Two methods are possible. The first method is to use the blockwise estimates directly available from the BSS process as described in relation to **FIG. 3** such as averaging across the blocks. A second method is to use the time stamps available from the blockwise correlation process **313** of particular eigenvalues as indexes into the digitizer buffer memory. Subsequently, the raw data so indexed is used to directly make an estimate of the steering vector. In both cases the steering vector will be estimated using the data available from the GEVD of the SFOCMP. Once steering vector estimates are available, the estimation of the other spatial variables, AoA and/or geolocation, can be determined by methods well-known in the art. The characteristic that allows this computation is that the eigenvalues and eigenvectors of the GEVD of the SFOCMP have a 1:1 correspondence as in standard eigenanalysis. So, when the eigenvalues are used to measure the high-order statistical properties of the received signals, an index relating directly to where that signal with that characteristic emanated from is available. Again, the spatial dimension for signal association can be exploited to remove any ambiguity of the temporal decomposition, since we assume that no two emitters are identically located.

[0085] Signal tracks **1021**, **1023** and **1025** containing associating matrix pencil eigenvalues from consistent sources as evident from common spatial variables are used to recover the message by correlating track information against spatial variables and time gates. This recovery process is performed by the covert communication receive processor **319**.

[0086] The recovered messages are composed of sequentially ordered matrix pencil eigenvalues with a duration within the time gate originating from the same location as determined by the steering vector estimate, AoA or geolocation. The “signal sequence 1” **1021** includes eigenvalues 1, 4, 7, 10, and 12 with durations mapping message “01011”, these eigenvalues and their associated signals all originated from a “consistent” spatial location, namely, Geo_1 , AoA_1 or had the same steering vector SV_1 . Similarly, “signal sequence 2” **1023** includes eigenvalues and durations with common steering vectors, AoA, or geolocation and the durations pass the time gate filter thus recovering a “000100” message. “Signal sequence 3” **1025** however had two eigenvalues 3 and 9 with high spatial correlation, however the signal is not decoded since the durations exceed the time gate allowable. In short, the receive processor recognized that the time durations in sequence **1025** do not correspond to any symbols of the expected alphabet.

[0087] The advantages of incorporating spatial variables into the message recovery process warrant explanation. First, the spatial variables aid in rejecting extraneous pulsed emitters based on their spatial locations being anti-correlated over time to the persistent spatial locations of the covert emitter(s). By the same token, spatial variables allow the basic signaling approach to support multiple access of covert emitters without undue burden in the receiver for properly assembling the pulsed message sequences. This is because the additional covert emitters will very likely emanate from resolvable spatial locations, and the receiver can use the consistency of the spatial locations over time to associate the proper message sequence. For each transmitted signal, the message sequence is represented by the time durations of the eigenvalues of the appropriately selected matrix pencil, where we have preferred the SFOCMP approach.

[0088] The spatial location of any emitter is independent of the exact value of its corresponding eigenvalues available from the GEVD of the SFOCMP. Lastly, the spatial variables provide additional “distance” in the recovery process, since it is now multi-dimensional. For example, two signals may have very similar eigenvalues. But, if their spatial locations are resolvable by the receiver, and fairly constant, then the eigenvalues corresponding to those spatial locations can be easily assigned. Then the message can be recovered using the time duration of each eigenvalue in the sequence assigned a given spatial location using the same technique as previously described when only a single covert signal was in view.

[0089] The ability to resolve spatial location has system implications that are interrelated. Some top-level practical design issues that must be reconciled, are desired proximity of transmitters, expected noise environment, block processing sample support for estimating spatial locations and the eigenvalues available from the SFOCMP, digitizer sample rates, signal bandwidths and center frequencies, aperture design (i.e. element type, size, number of ports, operating frequency), and the like. This is of course in addition to having an appropriate level of calibration and positional knowledge of the receive platform. Many of these considerations are direct carry-overs from standard array-based signal processing systems.

[0090] **FIG. 11** is a flow chart for covert communication with a transmitter **1102** and a receiver **1103** using message recovery with spatial information as shown in **FIG. 10**. The source **1100** provides a data stream to the covert transmitter **1102** as a stream of M-ary alphabet symbols. In block **1104** each M-ary alphabet symbol is assigned a unique duration. Plural waveforms with determinable high order statistic that are constant and non zero are generated in block **1106**. One of the plural waveforms is selected in block **1108** and is transmitted for the symbol assigned duration in block **1110**. In block **1112** it is determined if the transmitted symbol is the last in the message, if the last symbol has been transmitted the process is returned in block **1116** to standby or other quasi active state pending initiation of a new message. If other symbols remain to be transmitted, a different waveform from that previously transmitted is selected in block **1114** and transmitted for the respective symbols assigned duration in block **1110**.

[0091] The receiver **1103** receives the transmitted waveform along with environmental and random noise in a multi

element array as shown in block 1105. Using BSS and GEVD, matrix pencil eigenvalues (MPE) are obtained in block 1107 and the MPE are blockwise correlated to determine their respective durations in block 1109. A spatial variable or location is determined from the MPE in block 1111, again the spatial variable can be selected from a Steering vector, AoA or geolocation. The MPE detection durations are time gate filtered in block 1113 to reject detections outside of the duration minimum and maximum thresholds. The passed MPE and durations are sequentially sorted by common or consistent spatial variable in to signal tracks in block 1115. The signal tracks are maps are mapped (i.e. their durations are correlated to symbols and their respective assigned durations) to recover the message in block 1117. The message may be processed otherwise transformed to provide the message at the sink 1101.

[0092] If spatial data is unavailable, say because calibration of the sensing array has been degraded, the communication process can still operate. However, the freedom of waveform selection by the transmitter is reduced. In this case the transmitter must select a specific waveform type and use it exclusively (in a pulsed fashion) over the entire message (FIG. 4). Unfortunately with this implementation option the achievable data rate is reduced because of the need to introduce "deadtime" to define symbol boundaries. Thus it is possible to use a single "carrier waveform" that can be pulsed "ON" for each symbol followed by a period of "OFF" time. In this way the covert transmitter need only use a single waveform and need not modify its fourth-order cumulant signature. This could be an advantage in systems where additional spatial correlation variables preferred to aid unambiguous assignment of the received eigenvalues are unavailable, since we identify one and only one eigenvalue. But as mentioned this is disadvantageous in a multi-emitter environment. For such an environment we prefer a waveform agile emitter where the "carrier waveform" sequencer logic can be designed to select the "carrier waveform" for a specific duration, controlled by the message symbol, in either a fixed map or in some other manner. The mapping choice would be up to the transmitter designer and need not be known to the receiver. The receiver processing is shown in FIG. 12.

[0093] FIG. 12 presents a receiver 303 for processing covert messages without spatial location or spatial variable information. Processor 1201 contains BSS processing 309 and eigenvalue correlation 313 operating in the same manner as previously described, however without transferring or developing spatial variables. Therefore the eigenvalue characteristic and time stamps for determining eigenvalue duration are stored in the signal history database 317, without a spatial variable. For the embodiment of FIG. 12, the tracks are not sorted by spatial location by rather eigenvalues. Signal tracks contain only detections of the same eigenvalue with a detected duration that passes the time gate. Signal 1221 includes only one eigenvalue with 4 detection durations that pass the time gate. Signal 1221 thus is mapped to recover message "0010". The durations of the "OFF" period of pulse is irrelevant as long as its duration is greater than 1 block to enable the previous detection to be terminated the tracking correlator 313. Signal tracks 1223 and 1225 are both ignored or discarded for failing the time gate.

[0094] FIG. 13 is a flow chart for covert communication with a transmitter 1302 and a receiver 1303 using message

recovery without spatial information as shown in FIG. 12. The process is similar to that shown in FIG. 11. The source 1300 provides a data stream to the covert transmitter 1302 as a M-ary alphabet symbols. In block 1304 each M-ary alphabet symbol is assigned a unique duration. However, now a signal waveform with a determinable high order statistic that is constant and nonzero is generated in block 1306. The waveform is transmitted for the symbol assigned duration in block 1310. In block 1312 it is determined if the transmitted symbol is the last in the message, if the last symbol has been transmitted the process is returned in block 1316 to standby or other quasi active state pending initiation of a new message. If other symbols remain to be transmitted, the transmitter is paused, or another unique waveform is transmitted for an small duration $t=k$ in block 1320. The waveform generated in block 1306 is again transmitted for the respective symbol assigned duration in block 1310.

[0095] The receiver 1303 receives the transmitted waveform along with environmental and random noise in a multi element array as shown in block 1305. Using BSS and GEVD, matrix pencil eigenvalues are obtained in block 1307 and the MPE are tracked to determine their respective durations in block 1309. The MPE detection durations are time gate filtered in block 1313 to reject detections outside of the duration minimum and maximum thresholds. The passed MPE and durations are sequentially sorted by specific eigenvalue into signal tracks in block 1321. The eigenvalue durations forming the "signal sequences" are mapped (i.e., their durations are correlated to symbols and their respective assigned durations) to recover the message in block 1317 and delivered to the sink 1301.

[0096] FIG. 14 is a flow diagram for covert communication using encoded eigenvalues and spatial information. The source 1400 provides a data stream to the covert transmitter 1402 as a M-ary alphabet symbols. In block 1404 the M-ary symbols of the messages are encoded as MPE with unique durations. The eigenvalue is transmitted for the symbol assigned duration as a respective source waveform in block 1410. The source waveform is the low order signal whose high order statistic creates the respective eigenvalue. In block 1412 it is determined if the transmitted symbol is the last in the message, if the last symbol has been transmitted the process is returned in block 1416 to standby or other quasi active state pending initiation of a new message. If other symbols remain to be transmitted, a different MPE is selected in block 1414 and transmitted with a respective symbol assigned duration as a respective source waveform in block 1410.

[0097] The receiver 1403 receives the transmitted waveform along with environmental and random noise in a multi element array as shown in block 1405. Using BSS and GEVD, the matrix pencil eigenvalues encoding the symbol are recovered and tracked in block 1407 to determine their respective durations and spatial information in block 1409. The MPEs are decoded based on MPED and Spatial information as previously described in block 1417 to recover the message and provide the message symbols to the sink in block 1401. Generally the noise is white Gaussian noise, color noise or interferer signals.

[0098] FIG. 15 is a representation of a binary message sequence 101011 transmitted via data carrying waveforms according to an embodiment. In the embodiment shown the

symbol are transmitted by alternating waveforms of BPSK, QPSK and GMSK. As the message is independent of the encoded data, for LPI it is preferred that the carrier waveforms be modulated with random data at a rate greatly exceeding the covert message symbol rate. The random data may be modulated for a BPSK waveform at 5 sample/per random symbol with a frequency offset of $0.1 f_s$, for QPSK wave at 10 samples/random symbol with a frequency offset of $-0.05 f_s$ and for a GMSK waveform (GSM: $h_{mod} = 1/2$, $Bt_b = 1/3$) 2 samples/random symbol with a frequency offset of $0.0005 f_s$. Other waveforms including to DQPSK, DBPSK, FSK, QAM, DPCM are equally applicable and are also envisioned, however embodiments of the invention should not be construed to be limited to the particular waveforms listed.

[0099] As discussed previously the waveform duration discriminates the message symbol. As shown in FIG. 15 the symbol 1 has a duration of 20 blocks and the symbol "0" has a duration of 10 blocks. The message is transmitted as a GMSK waveform for a duration of 20 blocks indicating a symbol "1". The next symbol is transmitted as a different waveform QPSK for a duration of 10 block indicating a symbol "0". The next symbol is transmitted by the GMSK waveform for a duration of 20 blocks again indicating a "1" symbol and a QPSK waveform is used to transmit the "0" symbol. As illustrative of the independent of the waveform and message content the symbol "1" is then transmitted as a BPSK waveform for a 20 block duration and the next symbol "1" is transmitted by the QPSK waveform for a duration of 20 block. Evident in FIG. 15 is that identical waveforms can communicate different symbols while maintaining waveform content and message independence.

[0100] While preferred embodiments of the present inventive system and method have been described, it is to be understood that the embodiments described are illustrative only and that the scope of the embodiments of the present inventive system and method is to be defined solely by the appended claims when accorded a full range of equivalence, many variations and modifications naturally occurring to those of skill in the art from a perusal hereof.

We claim:

1. A communication device for providing a communication signal from a data signal comprised of a sequence of bits, comprising:

- a noise generator for generating a first signal comprised of a bit stream;
- a filter for receiving said first signal and generating a temporal dependence between immediately adjacent bits in said first signal to thereby provide a third signal;
- a plurality of signal sources each providing a source signal with a characteristic unique from the others;
- a switch for selectively operatively connecting as a function of said data signal one of said plurality of signal sources in sequence to a combining means to thereby provide a second signal; and

said combining means for combining said third signal with said second signal to thereby provide the communication signal from said data signal.

2. The communication device of claim 1 wherein said noise generator is a Laplacian noise generator.

3. The communication device of claim 1 wherein said noise generator generates a signal with a distribution function for which the kurtosis is greater than the kurtosis of a Gaussian distribution function.

4. The communication device of claim 1 wherein said noise generator generates a signal with a distribution function for which the kurtosis is different than the kurtosis of a Gaussian distribution function.

5. The communication device of claim 1 wherein said filter is a spectral limiting filter.

6. The communication device of claim 1 wherein said filter is selected from the group consisting of an autoregressive filter, an infinite impulse response filter combined with a low pass filter, and a finite impulse response filter with a moving average.

7. The communication device of claim 1 wherein said characteristic is from the group consisting of frequency, waveform, matrix pencil eigenvalue, phase noise, I/Q imbalance, timing jitter, phase jitter, symbol rate, pulse shape, a fourth-order statistic, relative rotational alignment of a signal constellation, power amplifier rise/fall time, and Doppler shift.

8. The communication device of claim 1 wherein said characteristic is a waveform from the group consisting of BPSK, QPSK, GMSK, QAM, DBPSK MFSK, FSK, and DQPSK waveforms.

9. The communication device of claim 1 wherein said characteristic is a waveform with a matrix pencil eigenvalue that is a function of the spatial second order moment of said waveform.

10. The communication device of claim 1 wherein said characteristic is a waveform with a matrix pencil eigenvalue that is a function of the spatial fourth order cumulant of said waveform.

11. The communication device of claim 1 wherein at least one of said plurality of signal sources is from the group consisting of an oscillator, a random signal generator, and a Laplacian noise generator.

12. The communication device of claim 1 wherein said combining means is a logic circuit.

13. The communication device of claim 1 wherein said combining means is from the group consisting of a mixer, a multiplier, a divider, and an adder.

14. The communication device of claim 1 wherein said communication signal has a received SNR less than 0 dB.

15. The communication device of claim 1 wherein said communication signal has a SNIR less than 0 dB at the intended receiver.

16. The communication device of claim 1 further comprising circuitry for forming symbols of an M-ary alphabet by assigning sequentially to each of said symbols a predetermined number of bits of said data signal.

17. The communication device of claim 16 wherein said predetermined number of bits is from the group consisting of positive integers.

18. The communication device of claim 16 wherein said communication signal is comprised of symbols of said M-ary alphabet.

19. The communication device of claim 18 wherein each of said symbols in said M-ary alphabet has a time duration unique among said alphabet.

20. The communication device of claim 19 wherein for each of said symbols said switch operatively connects one of

said plural signal sources other than the signal source operatively connected for the immediately preceding symbol.

21. The communication device of claim 20 wherein said switch operatively connects one of said plural signal sources for the duration of the respective symbol.

22. The communication device of claim 1 wherein said first signal includes an I signal and a Q signal.

23. The communication device of claim 1 further comprising radio frequency processing circuitry for processing said communication signal for transmission.

24. The communication device of claim 23 further comprising a radio frequency transmitter and antenna for transmitting said communication signal.

25. A communication device for providing a communication signal from a sequence of bits comprising:

first means for providing a first signal;

second means for providing a second signal comprising, in sequence, as a function of said sequence of bits, one of a plurality of third signals each with a matrix pencil eigenvalue unique among said third signals; and

third means for combining said first and second signals to thereby provide the communication signal.

26. The communication device of claim 25 further comprising circuitry for forming symbols of an M-ary alphabet by assigning sequentially to each of said symbols a predetermined number of bits in said sequence of bits.

27. The communication device of claim 26 wherein said predetermined number of bits is from the group consisting of positive integers.

28. The communication device of claim 26 wherein said communication signal is comprised of symbols of said M-ary alphabet.

29. The communication device of claim 28 wherein each of said symbols in said M-ary alphabet has a time duration unique among said alphabet.

30. The communication device of claim 29 wherein said first means comprises a noise generator for providing a noise signal of which said first signal is a function thereof.

31. The communication device of claim 30 wherein said first means further comprises a filter for receiving said noise signal and producing therefrom a signal with temporal dependence between adjacent bits of said noise signal to thereby provide said first signal.

32. The communication device of claim 31 wherein said second means comprises a plurality of signal sources each providing one of said plurality of third signals.

33. The communication device of claim 32 wherein said second means further comprises a first switch for operatively connecting for each of said symbols one of said plural signal sources other than the signal source operatively connected for the immediately preceding symbol to thereby provide said second signal.

34. The communication device of claim 33 wherein said noise generator is a plurality of noise generators the outputs of which are operatively connected to a second switch which operates synchronously with said first switch to thereby provide said noise signal.

35. The communication device of claim 33 wherein said noise generator is a plurality of noise generators the outputs of which are operatively connected to a second switch which operates asynchronously with said first switch to thereby provide said noise signal.

36. The communication device of claim 33 wherein said filter is a plurality of filters the inputs of which are operatively connected to a second switch which receives said noise signal and which operates synchronously with said first switch to thereby provide said first signal.

37. The communication device of claim 33 wherein said filter is a plurality of filters the inputs of which are operatively connected to a second switch which receives said noise signal and which operates asynchronously with said first switch to thereby provide said first signal.

38. The communication device of claim 33 wherein said noise generator is a plurality of noise generators and said filter is a plurality of filters whereby each noise generator is operatively connected to one of said plurality of filters, wherein the outputs of said filters are operatively connected to a second switch which operates synchronously with said first switch to thereby provide said first signal.

39. The communication device of claim 33 wherein said noise generator is a plurality of noise generators and said filter is a plurality of filters whereby each noise generator is operatively connected to one of said plurality of filters, wherein the outputs of said filters are operatively connected to a second switch which operates asynchronously with said first switch to thereby provide said first signal.

40. The communication device of claim 29 wherein said first means comprises a signal source for providing said first signal.

41. The communication device of claim 40 wherein said second means comprises a plurality of noise generators each providing one of said plurality of third signals.

42. The communication device of claim 41 wherein said second means further comprises a first switch for operatively connecting for each of said symbols one of said plural noise generators other than the noise generator operatively connected for the immediately preceding symbol to thereby provide said second signal.

43. The communication device of claim 41 wherein each of said noise generators includes a filter for providing temporal dependence between immediately adjacent bits in the associated said third signal.

44. The communication device of claim 29 further comprising a filter for receiving said communication signal and producing therefrom a second communication signal with temporal dependence between adjacent symbols of said second communication signal.

45. The communication device of claim 29 wherein said first signal comprises a noise signal with a Laplacian distribution with temporal dependence between adjacent bits of said noise signal.

46. The communication device of claim 29 wherein said first signal comprises a noise signal with temporal dependence between adjacent bits of said noise signal and with a distribution function for which the kurtosis is greater than the kurtosis of a Gaussian distribution function.

47. The communication device of claim 29 wherein said first signal comprises a noise signal with temporal dependence between adjacent bits of said noise signal and with a distribution function for which the kurtosis is different than the kurtosis of a Gaussian distribution function.

48. In a receiver including an antenna with a plurality of antenna elements for receiving a communication signal comprised of a plurality of symbols and a digitizer for providing a bit stream from the received symbols, the

improvement comprising a filter for generating a temporal dependence between immediately adjacent bits of said bit stream.

49. The receiver of claim 48 wherein the improvement further comprises means for determining a matrix pencil eigenvalue for at least one of said symbols.

50. The receiver of claim 49 wherein the improvement further comprises means for determining the generalized eigenvalue decomposition of said matrix pencil eigenvalue.

51. The receiver of claim 50 wherein the improvement further comprises means for determining the duration of said matrix pencil eigenvalue.

52. The receiver of claim 51 wherein the improvement further comprises means for filtering said symbols as a function of the determined duration of the associated matrix pencil eigenvalue.

53. The receiver of claim 52 wherein the improvement further comprises means for spatially correlating the filtered matrix pencil eigenvalues.

54. The receiver of claim 53 wherein the improvement further comprises means for sequentially mapping the correlated matrix pencil eigenvalues.

55. A communication system comprising a transmitter and a receiver geographically separated from the transmitter for communicating a communication signal formed from a sequence of bits wherein said communication signal is comprised of a plurality of symbols, comprising:

a transmitter comprising:

first means for providing a first signal;

second means for providing a second signal comprising in sequence as a function of said sequence of bits one of a plurality of third signals each with a matrix pencil eigenvalue unique among said third signals;

third means for combining said first and second signals to thereby provide said communication signal; and

transmitting means for transmitting said communication signal; and

a receiver comprising:

receiving means for receiving and digitizing the symbols of said communication signal to thereby produce a first received signal;

means for determining a matrix pencil eigenvalue for at least one of said first received signal symbols;

means for determining the generalized eigenvalue decomposition of said matrix pencil eigenvalue;

means for determining the duration of said matrix pencil eigenvalue; [ditto]

means for filtering said symbols as a function of the determined duration of the associated matrix pencil eigenvalue; [ditto]

means for spatially correlating the filtered matrix pencil eigenvalues; and

means for sequentially mapping the correlated matrix pencil eigenvalues to thereby determine at the receiver the sequence of bits in the communication signal.

56. The communication system of claim 55 further comprising at the receiver means for determining a spatial variable of said matrix pencil eigenvalue.

57. The communication system of claim 56 wherein said spatial variable is a steering vector.

58. The communication system of claim 57 further comprising at the receiver means for determining the angle of arrival of the communication signal as a function of said steering vector.

59. The communication system of claim 58 further comprising at the receiver means for determining the geolocation of said transmitter as a function of said steering vector.

60. A communication system comprising a transmitter and a receiver geographically separated from the transmitter for communicating a communication signal formed from a sequence of bits wherein said communication signal is comprised of a plurality of symbols, comprising:

a transmitter comprising:

first means for providing a first signal;

second means for providing a second signal comprising in sequence as a function of said sequence of bits one of a plurality of third signals each with a matrix pencil eigenvalue unique among said third signals;

third means for combining said first and second signals to thereby provide said communication signal; and

transmitting means for transmitting said communication signal; and

a receiver comprising:

receiving means for receiving and digitizing the symbols of said communication signal to thereby produce a first received signal;

means for determining a matrix pencil eigenvalue for at least one of said first received signal symbols;

means for determining the generalized eigenvalue decomposition of said matrix pencil eigenvalue;

means for determining the duration of said matrix pencil eigenvalue;

means for filtering said symbols as a function of the determined duration of the associated matrix pencil eigenvalue;

means for sorting the filtered matrix pencil eigenvalues into at least one group of like eigenvalues; and

means for sequentially mapping the correlated matrix pencil eigenvalues to thereby determine at the receiver the sequence of bits in the communication signal.

61. A method for providing a communication signal from a data signal comprised of a sequence of bits, comprising the steps of:

providing a first signal comprised of a bit stream;

receiving said first signal and generating a temporal dependence between immediately adjacent bits in said first signal to thereby provide a third signal;

providing a plurality of signal sources each providing a source signal with a characteristic unique from the others;

providing a combining means;

selectively operatively connecting as a function of said data signal one of said plurality of signal sources in sequence to said combining means to thereby provide a second signal; and

combining at said combining means said third signal with said second signal to thereby provide the communication signal from said data signal.

62. The method of claim 61 wherein said first signal has a Laplacian distribution function.

63. The method of claim 61 wherein said first signal has a distribution function for which the kurtosis is greater than the kurtosis of a Gaussian distribution function.

64. The method of claim 61 wherein said first signal has a distribution function for which the kurtosis is different than the kurtosis of a Gaussian distribution function.

65. The method of claim 61 wherein said characteristic is from the group consisting of frequency, waveform, matrix pencil eigenvalue, phase noise, I/Q imbalance, timing jitter, phase jitter, symbol rate, pulse shape, a fourth-order statistic, relative rotational alignment of a signal constellation, power amplifier rise/fall time, and Doppler shift.

66. The method of claim 61 wherein said characteristic is a waveform from the group consisting of BPSK, QPSK, GMSK, QAM, DBPSK MFSK, FSK, and DQPSK waveforms.

67. The method of claim 61 wherein said characteristic is a waveform with a matrix pencil eigenvalue that is a function of the spatial second order moment of said waveform.

68. The method of claim 61 wherein said characteristic is a waveform with a matrix pencil eigenvalue that is a function of the spatial fourth order cumulant of said waveform.

69. The method of claim 61 wherein said communication signal has a received SNR less than 0 dB.

70. The method of claim 61 wherein said communication signal has a SNIR less than 0 dB at the intended receiver.

71. The method of claim 61 further comprising the step of forming symbols of an M-ary alphabet by assigning sequentially to each of said symbols a predetermined number of bits of said data signal.

72. The method of claim 71 wherein said predetermined number of bits is from the group consisting of positive integers.

73. The method of claim 71 wherein said communication signal is comprised of symbols of said M-ary alphabet.

74. The method of claim 73 wherein each of said symbols in said M-ary alphabet has a time duration unique among said alphabet.

75. The method of claim 74 wherein for each of said symbols the step of selectively operatively connecting is accomplished so that one of said plural signal sources other than the signal source for the immediately preceding symbol is operatively connected.

76. The method of claim 75 wherein the step of selectively operatively connecting is accomplished such that one of said plural signal sources is operatively connected for the duration of the respective symbol.

77. The method of claim 71 wherein said first signal includes an in-phase signal and a quadrature signal.

78. The method of claim 71 further comprising the step of processing said communication signal for radio frequency transmission.

79. The method of claim 78 further comprising the step of transmitting said communication signal.

80. A method for providing a communication signal from a sequence of bits comprising:

providing a first signal;

providing a second signal comprising, in sequence, as a function of said sequence of bits, one of a plurality of third signals each with a matrix pencil eigenvalue unique among said third signals; and

combining said first and second signals to thereby provide the communication signal.

81. The method of claim 80 further comprising the step of forming symbols of an M-ary alphabet by assigning sequentially to each of said symbols a predetermined number of bits in said sequence of bits.

82. The method of claim 81 wherein said predetermined number of bits is from the group consisting of positive integers.

83. The method of claim 81 wherein said communication signal is comprised of symbols of said M-ary alphabet.

84. The method of claim 83 wherein each of said symbols in said M-ary alphabet has a time duration unique among said alphabet.

85. The method of claim 84 wherein said first signal is comprised of a noise signal of which said first signal is a function thereof.

86. The method of claim 85 wherein said noise signal is produced with temporal dependence between adjacent bits to thereby provide said first signal.

87. The method of claim 86 wherein said second signal is comprised of a sequential combination of a plurality of third signals provided by a corresponding plurality of signal sources.

88. The method of claim 87 wherein the step of providing said second signal is accomplished by operatively connecting said third signals to a first switch whereby for each of said symbols said switch operatively connects one of said third signals other than the third signal that was operatively connected for the preceding symbol.

89. The method of claim 88 wherein said noise signal is a plurality of noise signals which are operatively connected to a second switch which operates synchronously with said first switch to thereby provide said noise signal.

90. The method of claim 88 wherein said noise signal is a plurality of noise signals which are operatively connected to a second switch which operates asynchronously with said first switch to thereby provide said noise signal.

91. The method of claim 88 wherein said temporal dependence between adjacent bits of said noise signal is provided by a plurality of filters arranged in parallel the inputs of which are operatively connected to a second switch which receives said noise signal and which operates synchronously with said first switch to sequentially operatively connect one of said plurality of filters to thereby provide said first signal.

92. The method of claim 88 wherein said temporal dependence between adjacent bits of said noise signal is provided by a plurality of filters arranged in parallel the inputs of which are operatively connected to a second switch which receives said noise signal and which operates asyn-

chronously with said first switch to sequentially operatively connect one of said plurality of filters to thereby provide said first signal.

93. The method of claim 88 wherein said noise signal is a plurality of noise signals and said temporal dependence between adjacent bits of said noise signal is provided by a corresponding plurality of filters arranged in parallel whereby each said noise signal is operatively connected to one of said plurality of filters wherein the outputs of said filters are operatively connected to a second switch which operates synchronously with said first switch to thereby provide said first signal.

94. The method of claim 88 wherein said noise signal is a plurality of noise signals and said temporal dependence between adjacent bits of said noise signal is provided by a corresponding plurality of filters arranged in parallel whereby each said noise signal is operatively connected to one of said plurality of filters wherein the outputs of said filters are operatively connected to a second switch which operates asynchronously with said first switch to thereby provide said first signal.

95. The method of claim 84 wherein said first signal is provided by a signal source.

96. The method of claim 95 wherein said second signal is provided by a first switch for operatively connecting for each of said symbols one of said third signals other than the noise signal operatively connected for the immediately preceding symbol.

97. The method of claim 96 wherein for each of said third signals the unique matrix pencil eigenvalue is a function of the temporal dependence between immediately adjacent bits provided by a filter.

98. The method of claim 84 further comprising the step of providing temporal dependence between adjacent bits of said communication signal and producing therefrom a second communication signal.

99. The method of claim 98 wherein the temporal dependence is provided by a filter.

100. The method of claim 84 wherein said first signal comprises a noise signal with a Laplacian distribution with temporal dependence between adjacent bits of said noise signal.

101. The method of claim 84 wherein said first signal comprises a noise signal with temporal dependence between adjacent bits of said noise signal and with a distribution function for which the kurtosis is greater than the kurtosis of a Gaussian distribution function.

102. The method of claim 84 wherein said first signal comprises a noise signal with temporal dependence between adjacent bits of said noise signal and with a distribution function for which the kurtosis is different than the kurtosis of a Gaussian distribution function.

103. In a method of receiving a communication signal comprised of a plurality of symbols in a receiver including an antenna with a plurality of antenna elements and a digitizer for providing a bit stream from the received symbols, the improvement comprising the step of providing a temporal dependence between immediately adjacent bits of said bit stream.

104. The method of claim 103 wherein the improvement further comprises the step of determining a matrix pencil eigenvalue for at least one of said symbols.

105. The method of claim 104 wherein the improvement further comprises the step of determining the generalized eigenvalue decomposition of said matrix pencil eigenvalue.

106. The method of claim 105 wherein the improvement further comprises the step of determining the duration of said matrix pencil eigenvalue.

107. The method of claim 106 wherein the improvement further comprises the step of filtering said symbols as a function of the determined duration of the associated matrix pencil eigenvalue.

108. The method of claim 107 wherein the improvement further comprises the step of spatially correlating the filtered matrix pencil eigenvalues.

109. The method of claim 108 wherein the improvement further comprises the step of sequentially mapping the correlated matrix pencil eigenvalues.

110. A method of communicating between a transmitter and a receiver including a multi-element array antenna which is geographically spaced apart from said transmitter a communication signal formed from a sequence of bits wherein said communication signal is comprised of a plurality of symbols, comprising the steps of:

in the transmitter:

providing a first signal;

providing a second signal comprising in sequence as a function of said sequence of bits one of a plurality of third signals each with a matrix pencil eigenvalue unique among said third signals;

combining said first and second signals to thereby provide said communication signal; and

transmitting said communication signal; and

in the receiver:

receiving and digitizing the symbols of said communication signal to thereby produce a first received signal;

determining a matrix pencil eigenvalue for at least one of said first received signal symbols;

determining the generalized eigenvalue decomposition of said matrix pencil eigenvalue;

determining the duration of said matrix pencil eigenvalue;

filtering said symbols as a function of the determined duration of the associated matrix pencil eigenvalue;

spatially correlating the filtered matrix pencil eigenvalues; and

sequentially mapping the correlated matrix pencil eigenvalues to thereby determine at the receiver the sequence of bits in the communication signal.

111. The method of claim 110 wherein the step of determining the matrix pencil eigenvalue for a received symbol includes the step of determining a spatial second-order moment.

112. The method of claim 110 wherein the step of determining the matrix pencil eigenvalue for a received symbol includes the step of determining a spatial fourth-order cumulant.

113. The method of claim 110 further comprising the step of determining a spatial variable of said matrix pencil eigenvalue.

114. The method of claim 113 wherein said spatial variable is a steering vector of the communication signal.

115. The method of claim 114 further comprising at the receiver the step of determining the angle of arrival of the communication signal as a function of said steering vector.

116. The method of claim 114 further comprising at the receiver the step of determining the geolocation of said transmitter as a function of said steering vector.

117. The method of claim 110 wherein said first signal is a noise signal comprised of a bit stream with a Laplacian distribution with temporal dependence between immediately adjacent bits.

118. The method of claim 110 wherein each of said third signals has a unique frequency among said third signals.

119. The method of claim 110 wherein each of said third signals has a unique waveform among said third signals.

120. The method of claim 119 wherein said waveforms are from the group consisting of BPSK, QPSK, GMSK, QAM, DBPSK MFSK, FSK, and DQPSK waveforms.

121. The method of claim 119 further comprising the step of modulating the waveform of at least one of said third signals with random data at a rate substantially exceeding the rate of said sequence of bits.

122. The method of claim 119 further comprising the step of modulating the waveform of at least one of said third signals with data from a third communication signal.

123. The method of claim 110 wherein the step of receiving and digitizing includes the step of organizing the digitized bits into blocks of data comprised of sequential snapshots wherein said snapshots are each comprised of a bit from each element of said multi-element array antenna

124. The method of claim 123 wherein the matrix pencil eigenvalue is determined from said blocks of data.

125. The method of claim 124 wherein said block of data includes approximately 5000 snapshots.

126. The method of claim 125 wherein said duration of matrix pencil eigenvalues is the number of sequential blocks of data with approximately the same matrix pencil eigenvalue.

127. The method of claim 110 wherein the communication signal has a received SNR less than 0 dB.

128. The method of claim 110 wherein the communication signal has a SNIR less than 0 dB at the receiver.

129. The method of claim 110 wherein the communication signal has a SNIR less than -6 dB at the receiver.

130. The method of claim 110 wherein said sequence of third signals is determined at random.

131. The method of claim 110 wherein said sequence of third signals is predetermined.

132. A method of communicating between a transmitter and a receiver including a multi-element array antenna which is geographically spaced apart from said transmitter a communication signal formed from a sequence of bits wherein said communication signal is comprised of a plurality of symbols, comprising the steps of:

in the transmitter:

providing a first signal;

providing a second signal comprising in sequence as a function of said sequence of bits one of a plurality of

third signals each with a matrix pencil eigenvalue unique among said third signals;

combining said first and second signals to thereby provide said communication signal; and

transmitting said communication signal; and

in the receiver:

receiving and digitizing the symbols of said communication signal to thereby produce a first received signal;

determining a matrix pencil eigenvalue for at least one of said first received signal symbols;

determining the generalized eigenvalue decomposition of said matrix pencil eigenvalue;

determining the duration of said matrix pencil eigenvalue;

filtering said symbols as a function of the determined duration of the associated matrix pencil eigenvalue;

sorting the filtered matrix pencil eigenvalues into at least one group of like eigenvalues; and

sequentially mapping the correlated matrix pencil eigenvalues to thereby determine at the receiver the sequence of bits in the communication signal.

133. A method of communicating information comprised of a sequence of bits from a transmitter to a receiver comprising the steps of:

modulating a carrier wave with a data signal to thereby produce a first signal wherein the data signal does not represent the information to be communicated;

transmitting the first signal from the transmitter;

receiving the first signal at the receiver;

determining at the receiver the communicated information independently of the data signal.

134. The method of claim 133 wherein the step of determining the communicated information is performed without demodulating the first signal.

135. The method of claim 133 further comprising the step of providing a second signal with temporal dependence between immediately adjacent bits and combining said second signal with said modulated carrier wave to thereby produce said first signal.

136. The method of claim 135 further comprising the steps of:

sequentially grouping a predetermined number of bits in said sequence of bits into symbols to thereby provide symbols of an M-ary alphabet;

providing a plurality of third signals each with a matrix pencil eigenvalue unique among said third signals;

providing a switch whereby for each of said symbols said switch operatively connects one of said third signals other than the third signal that was operatively connected for the preceding symbol to thereby form said second signal.

137. The method of claim 136 wherein each of said symbols in said M-ary alphabet has a time duration unique among said alphabet.

138. The method of claim 137 wherein said information is communicated to the receiver as a function of the durations of said symbols in said M-ary alphabet.

139. In a method of communicating information from a transmitter to a receiver using a communication signal comprised of a carrier wave modulated by a data signal, the improvement comprising determining the information at the receiver independent of the data signal.

140. In a method of communicating information from a transmitter to a receiver using a communication signal containing a plurality of symbols comprised of a carrier wave modulated by a data signal, the improvement comprising determining the information at the receiver as a function of a higher-order statistic of the received symbols.

141. The method of claim 140 wherein said symbols comprise an M-ary alphabet and said higher-order statistic for each symbol in the M-ary alphabet is unique among said alphabet.

142. The method of claim 140 wherein said information includes a spatial variable.

143. In a method of communicating a first information stream from a transmitter to a receiver using a communication signal containing a plurality of symbols comprised of a carrier wave modulated by a data signal, the improvement comprising communicating a second information stream from the transmitter to the receiver by selectively altering a characteristic of said communication signal wherein said second information stream is different than said first information stream.

144. The method of claim 143 wherein said characteristic is from the group consisting of frequency, waveform, matrix pencil eigenvalue, phase noise, I/Q imbalance, timing jitter, phase jitter, symbol rate, pulse shape, a fourth-order statistic, relative rotational alignment of a signal constellation, power amplifier rise/fall time, and Doppler shift.

145. In a method of communication using plural waveforms where the duration of the transmission of each waveform represents a symbol, the improvement wherein the duration of transmission is determined by the state of a high-order statistic of a characteristic of the waveforms.

146. The method of claim 145 wherein said high-order statistic is a spatial second-order moment.

147. The method of claim 145 wherein said high-order statistic is a spatial fourth-order cumulant.

148. A method for communication of a message comprising a plurality of sequenced M-ary alphabet symbols, said method comprising the steps of:

assigning each M-ary alphabet symbol a unique symbol duration;

generating a waveform for which both the spatial 2nd order moment or the spatial 4th order cumulant are constant and not zero; and

for each symbol, transmitting the waveform for the assigned symbol duration immediately followed by a pause in waveform transmission.

149. A method for communication of a message comprising a plurality of sequenced M-ary alphabet symbols, said method comprising the steps of:

assigning each M-ary alphabet symbol a unique symbol duration;

generating plural waveforms for which the spatial 2nd order moment and the spatial 4th order cumulant are constant, nonzero, and unique; and

for each symbol, transmitting one of the plural waveforms for the assigned symbol duration so that immediately adjacent symbols are transmitted by different waveforms.

150. A method for communicating a message comprising a plurality of sequenced M-ary alphabet symbols represented by M-ary durations, said method comprising the steps of:

receiving a signal in a multiple element array;

determining a high order statistic of a signal characteristic of each symbol, and determining the duration of each symbol by the state of the determined high order statistic.

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