AN APPLICATION OF A DISPOSABLE REMOTE CHEMICAL SENSOR NETWORK

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Abstract- This paper addresses system engineering and mission planning issues for a disposable remote chemical sensor network. Engineering considerations include orbital analysis, telemetry, satellite transponder access, modulation techniques, power for remotes, a frequency plan, antennae selection, and verification that performance is feasible and acceptable via link budgets.

In this paper the objective will be to discuss all major technical considerations entailed in a preliminary system engineering of a disposable, remote chemical sensor network. The first of these considerations is the following: How does one most effectively sense the presence of chemical agents or hazardous chemicals in a local area and communicate indications of their presence to appropriate parties that need to take the necessary precautions? The current consensus appears to be that there are three generally accepted chemical sensor techniques, those being electrochemical sensors, ion mobility spectroscopy, and surface acoustic wave (SAW) sensors.

In the electrochemical sensing method chemical vapors are ionized via a radioactive source. The ionized vapors then pass through an electromagnetic field, where different chemicals are distinguished according to their differences in electrical charge and resulting characteristic residence times in the electromagnetic field.

Ion mobility spectroscopy distinguishes between chemicals via differences in charge and mass of ionized vapors in their flight paths.

SAW sensors distinguish between chemicals via frequency shifts. SAW devices are each impregnated with polymer coatings. Each SAW array of devices can number two or four, but is more commonly four. The chemical identity of each polymer coating must be known because there exist more than four polymer coating types that are used for this application, and consequently the grouping of four polymer coatings in a SAW array can vary. Generally speaking, the larger the concentration of foreign chemical affixing itself to the surface of a SAW device's polymer coating, the larger will be the corresponding frequency shift. An empirically determined database must be called upon to properly evaluate the chemical patterns in order that the hazardous foreign chemical agent or chemical may be correctly identified ([1],[2]).

Once the presence of undesired chemicals has been sensed, how can this information be most effectively disseminated to the appropriate interested parties? Three obvious communication options would be the following:

- (1) transmission of chemical information from remote chemical sensors to land-based transponder via a terrestrial communication link.
- (2) transmission of chemical information from remote chemical sensors to an airborne transponder; and
- (3) transmission of chemical information from remote chemical sensors on the surface of the earth to low-earth orbiting (LEO) satellite(s).

Option (1) appears the least attractive, mainly due to the higher prospect of detection for remote antenna patterns with large sidelobes and the high prospect of multipath fading as the transmitted signal propagates very closely to the earth. Option (2) to suffer from the same disadvantages as does Option (1), although in a less pronounced fashion -- particularly with respect to multipath fading because the signal will not propagate as closely to the earth. Finally, Option (3) appears to afford the highest prospect of the three for favorable performance, as it offers the least likelihood of line-of-sight obstruction, multipath fading, and detection of the large-sidelobed antenna pattern emanating from remote sensors. Since Option (3) is the most attractive, the remainder of this paper will focus on that satellite-based option. In order to ensure the success of Option (3), as a minimum the following preliminary system engineering would be examined:

- (1) execution of an orbital analysis to determine the number of satellites, and satellite traits, e.g., velocity, orbital period, stabilization error, satellite availability to remotes, and antenna coverage;
- (2) selection of antenna types for both the LEO satellites and remote sensors that will provide antenna patterns consistent with the mission objectives;
- (3) data rates and telemetry definition;
- (4) determination of a well-suited transponder access that remote chemical sensors may use when transmitting to a LEO satellite;
- (5) selection of modulation techniques that are amenable low-cost, low-power remote sensors, i.e., spectrally efficient modulation techniques for power-limited transmission from remote to transponder and noncoherent detection of signals at remote sensors from a satellite;
- (6) selection of a power source for the remote sensors;
- (7) determination of a frequency plan for transmit and receive channels that ensures levels of interference no higher than the thermal noise floor and the corresponding bandwidth allocations;
- (8) verification of acceptable performance of communication links via figures of merit resulting from a link budget analysis.

Orbital Analysis

A polar, circular orbit of altitude 250 km was selected. Using Kepler's Laws the period of revolution was determined to be 89.46 minutes. With 3-axis stabilization and a satellite stabilization error of ± 5 degrees, maximum antenna coverage occurs at an antenna beamwidth of 158.4 degrees. An antenna beamwidth of 148.4 degrees from a distance of 250 km subtends a global arc of 31.57 degrees, referenced to the earth's center. This arc on the earth's surface is 3514.3 km across, implying that at the satellite's velocity of 7.75 km/sec a duration of 453.46 seconds is needed to traverse the arc. 100 % LEO satellite availability would then require 12 satellites. Similarly 50 % satellite availability requires 6 LEO satellites. The distance from the satellite to its point of tangency with the earth, i.e., its slant range, is 1803.2 km at an elevation angle of about one degree [3].

Selection of Antennae

In the case of the LEO satellite an antenna pattern approaching hemispheric is desired. On the other hand, the remote antennae can obtain greater gains in the face of power-limited emissions when they exhibit more directive antenna patterns. The recommended antenna selection for the LEO satellite would be a quadrifilar helix antenna, because it is light-weight, relatively small, has no ground plane and has a nearly hemispheric antenna pattern. The axial mode helical antenna is the choice for the remote because it has no ground plane and is also relatively small and light, while also appropriate for directive antenna patterns of maximum gain along the helical axis. It is also circularly polarized, which is a beneficial quality for satellite applications [4].

Data Rates and Telemetry Definition

Each of the three chemical sensors will have unique data rates and data structures. For example, in the case of the electrochemical sensor four bits are allocated. Two of these bits will indicate whether a safe threshold for one of the four nerve agents has been exceeded, whereas the other two bits will tell whether the threshold for blister agents has been surpassed. The ion mobility spectroscopy requires eighteen bits for its sensor data set, nine bits for nerve and nine for blister agents. Each set of nine bits identifies a nerve or blister agent, in addition to informing as to the severity of the exposure. A four-SAW sensor array requires 60 bits for its sensor data set, 15 for each SAW sensor. Each of the 15 bits communicates in a binary

format the magnitude of the frequency shift that resulted when the sensor's polymer coating became impregnated with the foreign chemical.

For each of the three chemical sensors overhead bits are allocated, in addition to bits attributed to the chemical sensing data sets for each -- for a total of 14 bits for the electrochemical sensor, 28 bits for the ion mobility spectroscopy, and 82 bits for the four-SAW array. The breakdown with respect to overhead bits is as follows:

- (1) one start and one stop bit,
- (2) a numerical identifier for each of the 100 sensors proposed for this remote chemical sensor network,
- (3) identity of the polymer coating used for each of the four SAW sensors in the array that is only to be used for SAW arrays and no more than eight polymer coatings assumed for a total of three bits per SAW sensor), and
- (4) a preempt bit attributed to a chemically exposed sensor to preempt a sensor currently in communication mode that has not been exposed to a hazardous chemical.

Determination of an Advantageous Transponder Access Technique

In this section three prospective modes of LEO satellite transponder access will be examined: (1) random access, (2) Code Division Multiple Access (CDMA), and (3) adaptive polling with random burst transmission from the remote chemical sensors to the LEO satellite transponder -- a variant of Demand Assignment Multiple Access (DAMA) ([3],[7],[8]).

In a disposable, economical remote chemical sensor network, Option (1) has several disadvantages. From the standpoint of bandwidth requirements, in order to ensure that the incidence of collision is 10 % or less, the bandwidth needs can be as much as 20 times the information bandwidth (which is conservatively twice the data rate). "Collision" in this sense refers to two distinct remote sensor transmissions being received by the LEO satellite transponder simultaneously. This necessary increase in bandwidth for Option (1) would require proportionately greater power at the satellite, affecting adversely its compact size and low cost. Since in Option (1) remote sensors will continue to send signals so long as the satellite is in range, thereby enhancing the frequency of transmissions and the prospect of detection for the chemical sensors.

In the case of the CDMA option (Option 2), manufacturers of spread spectrum multiple access (SSMA) transmit and receive equipment were consulted on this proposed application. Each manufacturer stated that direct sequence (DS) spread spectrum would be more expensive than frequency hopped spread spectrum, whereas

the random burst transmit/receive technique would be cheaper to implement than either of the spread spectrum methods. Additional research in popular technical references corroborated these opinions ([5],[6]). In the case of the DS CDMA transponder, it calls for much more bandwidth than either the frequency hopped (FH) CDMA or random burst DAMA transponders. Also DS CDMA is typically implemented with coherent demodulation, that implies a more complex receiver design than is needed relative to the noncoherent demodulation of FH CDMA or random burst DAMA. The frequency hopping executed in FH CDMA necessitates the presence of a frequency synthesizer that is adept at switching carrier frequencies very rapidly, and its transponder must acquire and track the pseudorandom noise (PN) code (as does the DS CDMA transponder, but unlike the bursty DAMA transponder). Qualitatively speaking, it can be reasoned that the bursty DAMA transponder, having none of the weight-enhancing or cost-enhancing qualities of either SSMA technique, must be the most economical transponder of the three. Encryption hardware may be advised for each of these transponders. The bursty DAMA transponder could realize random burst and encrypted transmission qualities via chaotic circuits ([5],[6]). These embellishments of the bursty DAMA transponder would certainly render it the most desirable of the three transponder access methods considered here for applications calling for portability, disposability, and simplicity of design.

As a closing point on this section, the DAMA scenario will be discussed in more detail. The adaptive polling aspect of DAMA makes it an attractive application in instances where conservation of bandwidth is appreciated. Each of the proposed 100 transponders in the LEO satellite's antenna coverage area would be allocated a numerical identifier, which would conveniently reflect the order of access as the satellite traverses its coverage area. Each of the chemical remote sensors would be prompted for any chemical data it may have available to transmit, which would then be transmitted. If the chemical data does not indicate the presence of a hazardous chemical or chemical agent, the preempt bit previously mentioned is set to zero. If during the transmission of chemical data from sensor #1 (having no agents or hazardous chemicals in its vicinity) sensor #2 detects dangerous chemicals in its area, sensor #2 initiates contact with the LEO satellite overhead -- with the preempt bit of its overhead data set to one. This preempt bit value of one would then serve as an alarm to the LEO transponder, which would then cease communication with sensor #1 and commence receiving data from sensor #2. Upon completion of transmission from remote #2, the satellite would resume its polling sequence with the sensor that sequentially follows the preempting sensor, i.e., sensor #3. In this application sce-

nario the preempt bit becomes more or less priority level. If the priority of the transmitting sensor is zero, its transmission can superseded by a sensor whose preempt bit is one. On the other hand if a remote sensor of priority one is transmitting to the LEO transponder, its transmission cannot be interrupted by another sensor of priority one until its transmission is complete. The prioritization of the polling sequence according to the status of the preempt bit is what renders the polling process "adaptive." Each LEO satellite requires about 453 seconds to pass over its antenna coverage zone, which for a communication service with a 1% duty cycle implies that each of the 100 remote chemical sensors would have a 4.53 period in which to transmit, where the duration of transmission for each sensor would be no more than 0.0453 seconds (for hemispheric antenna pattern of transmission at the remote). The instant of transmission within this 4.53 second time slot would be decided randomly via chaotic circuits [5]. Were the remote's antenna pattern a more directive 45 degrees rather than hemispheric, the duration of transmission would be about 0.0113 seconds.

Finally, it is obvious in this application that jamming the correct sensor at precisely the correct instant would be very difficult. (The probability of successfully intercepting a sensor transmission with a jammer will vary from $1 \text{ E-}6$ for the hemispheric remote antenna pattern to $2.5 \text{ E-}7$ for a more directive 45 degree remote antenna pattern) ([3],[7],[8],[11]).

Selection of Modulation Techniques

Due to the limited power available at each of the chemical sensors, the transmit characteristics of any one of these sensors for modulation purposes are power-limited. Therefore, a power-efficient digital modulation technique that can be realized with a simple design will be selected for transmission from the chemical remote sensors. A modulation method well-advised for this application is coherent binary phase shift keying (BPSK). The receive function for the remote chemical sensor can be most economically realized with an envelope detector. The simplest receiver design with acceptable spectral efficiency can best be implemented with noncoherent frequency shift keyed (FSK) signal on the downlink from the LEO satellite to the remote chemical sensor [8].

Selecting a Power Source for the Remote Sensors

Lithium batteries from any of several prospective manufacturers seem able to supply power of two to three Watts. Three Watt power levels can be achieved with these batteries when the duty cycle is less than fifty per cent, which is the case in this application [9].

Frequency Plan and Bandwidth Allocations

The frequency plan's primary goal is to select transmit and receive frequencies for all nodes in the network, in such a way that anticipated levels of cochannel and adjacent channel interference are at or below the thermal noise floor. Such a plan is typically arrived at via an interference analysis and consultation with various references that cite the types of communication services that are entitled to each frequency band [10]. Once the receive and transmit center frequencies are determined for each node of a network, the bandwidth allocations can be defined -- with consideration given to modulation techniques used, data rates, Doppler shift due to a satellite's velocity, and frequency uncertainties due to frequency instabilities inherent in the communications hardware. After researching [10] and performing an interference analysis, the following frequencies were selected, as also indicated in Figure 1:

- (a) polling uplink (hub to LEO satellite): center frequency 2685 MHz with FSK modulation;
- (b) polling downlink (LEO satellite to remote chemical sensor): 400.13 MHz with FSK modulation;
- (c) return link (remote to LEO satellite): 469 MHz with coherent BPSK modulation; and
- (d) return link (LEO satellite to hub): 2650 MHz with coherent BPSK modulation.

Please note that Figures 2 and 3 provide the frequency allocations for the chemical network with the ion mobility spectroscopy (IMS) used as the chemical sensor. The electrochemical sensor and the SAW chemical sensor would have the same frequency allocations for frequency instabilities and Doppler shifts accounted for via guard bands, but owing to different data rates would exhibit different information bandwidths.

Assessment of the Proposed Network's Performance

Important factors in the assessment of the proposed chemical sensor network's performance will be reviewed here -- including figures of merit, prospect of successfully jamming in a military application, and relevant performance tradeoffs.

In the earlier section of this paper that addressed transponder access the randomly bursted, encrypted, adaptively polled transponder was deemed the most desirable in instances where disposability, portability, simplicity of design, and difficulty of compromise were criteria for selection of the bursty DAMA transponder over the DS CDMA and FH CDMA transponders. Additional tradeoffs can be posed with respect to the bursty DAMA transponder. Two of these tradeoffs would be the following:

- (1) Is it better to have a directive remote remote antenna pattern or a nondirective one?
- (2) Would transmitting or receiving signals at multiple frequencies alternately (to be distinguished from frequency hopping because here there are, unlike in frequency hopping, only a few different frequencies) mitigate compromise of communications additionally to the extent that their institution is justified?

These tradeoff issues can be resolved quickly. Equation (1) of Table I provides the reader with the mathematical definition of C/N_0 . In view of this equation a more directive antenna with the same power will offer the same quality of performance for C/N_0 because the increased remote gain is neutralized by the required faster data rate, which the remote must have to fully communicate its transmission to a satellite in the shorter transmission time associated with the narrower antenna beamwidth. However, the more directive antenna pattern addressed here would be more difficult to detect and, consequently, less subject to compromise.

As mentioned in the section on transponder access schemes, the probability of intercepting a signal to or from a remote and LEO satellite via a jammer is no more than 10^{-6} -- even if the frequency of transmission is known by the jammer. For this reason multiple frequencies of transmission would not significantly negate the already low probability of compromising communications from satellite to remote chemical sensor, or vice versa.

In summarizing the tradeoff conclusions, one can say that for military applications a more directive, narrower antenna beamwidth is more difficult to intercept and compromise, whereas performance, i.e., C/N_0 , will not be enhanced. In the scenario of tradeoff (2) as stated, there is no advantage to communicating at multiple frequencies.

To recapitulate on the proposed remote chemical sensor network's performance, this network -- with random bursts, encryption, and adaptive polling as portrayed -- should approach an optimum of performance, weight, portability, and simplicity of design at a low cost that affords the remote sensors disposability. Six simple, economical LEO satellites will provide only the hardware functions relevant to frequency translation from S-band to UHF-band, or vice versa. Satellites will be unavailable in this proposed configuration for no more than 7.56 minutes consecutively. The hub would provide the polling sequence to the various remote chemical sensors and perform any processing of the chemical sensor data. In the case of the SAW chemical sensor network, the pattern recognition algorithm necessary to identify any hazardous and/or lethal chemicals would be utilized at the hub. The proposed network would observe all important aspects of telemetry definition, data structure, orbital analysis, antenna configuration, transponder access, modulation

techniques, frequency plan, and bandwidth allocation as set forth in this and the previous sections of this paper.

Summary and Discussion of Results

Although not "secure" in the strict sense that it is not accommodated with both spread spectrum for resistance to jamming and encryption, the proposed chemical sensor network would be very difficult to effectively jam or otherwise compromise, primarily due to the physical separation of the chemical sensors over a large area, lack of a hostile's info as to remote destination and time of transmission from a LEO satellite to remote sensors, and the distance of the communicating satellite from prospective jammers. With the final resolution that this proposed chemical sensor network has a low prospect of compromise, attention can now be focused on communications of the network. The quality of communication links for this network will be evaluated via figures of merit for the network. These figures of merit are C/N_0 , E_b/N_0 , and link-margin. The ultimate measure of a communication link's performance, once the overall C/N_0 and E_b/N_0 for a polling link or return link of Figure 1 have been computed, reduces to a link margin result. For the typical communication link, a link margin of 3 dB to 5 dB is sufficient.

The algorithm, which leads to the computation of the link margin would proceed as follows. The combined uplink and downlink for a link budget are used in equation (2) to compute the overall C/N_0 for a single uplink and a single downlink, as indicated on equation (1) of Table I. The overall performance of the link budget, from the hub to satellite or vice versa, is then calculated via equation ((2) of the same table. The overall C/N_0 , carrier power to noise density is then translated to a bit energy to noise density ratio, E_b/N_0 , as in equation (3) of Table I. Once the E_b/N_0 for the overall link of interest is available, the engineer will then probably use the probability of bit error (BER) equation for either binary phase shift keying or noncoherent frequency shift keying (FSK) to determine what E_b/N_0 value will yield 1.0×10^{-5} and 1×10^{-6} probabilities of bit error (equations (4) and (5) of Table I). Then the engineer will compute the difference between the actual E_b/N_0 and the E_b/N_0 required to achieve 1.0×10^{-5} or 1.0×10^{-6} probabilities of bit error (equations (6) and (7) of Table I).

Utilizing the algorithm of Table I the link margin results of Table III indicate, as one would suspect, that the network links implementing the ion mobility spectroscopy variant of chemical sensor demonstrate a greater link margin on both the polling and return links than do the network links that use SAW devices as their chemical sensors. This is so primarily due to the higher data rates

that were necessary to characterize the chemical results as measured at the SAW sensors, in order that sufficient information could be supplied to the pattern recognition algorithm to be used at the hub's computer to evaluate SAW chemical results. Nevertheless, the link margin results for both the chemical sensor networks using the ion mobility spectroscopes and SAW sensors as their chemical sensors demonstrated link margins significantly in excess of 5.0 dB, thereby pointing out the feasibility of such a chemical sensor network in a real world application.

The sensor with the lowest data rates, in this case the electrochemical sensor, will necessarily exhibit a greater link margin than either the SAW or IMS sensor links.

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←----- FUGA, 1982-1983 -----→

←----- **WALKING DOWN** -----→ ←----- **STANDING UP** -----→

• Table I - Equations for the Computation of Link Margin

$$\begin{aligned}
 C_{No} &= [P_{avg}G_{ant}L_{md}]/((4\pi R)^2) \text{ and } L_{md} = 20 \log(1/\cos(\theta)) & (1) \\
 L(C_{No})_{total} &= L(C_{No})_{rx} - L(C_{No})_{jd} & (2) \\
 E_b/N_0 &= C_{No}/R & (3) \\
 P_z &= Q((E_b/N_0)^{0.5}) \text{ for BPSK modulation} & (4) \\
 P_z &= 1/2 \exp(-E_b/N_0) \text{ for noncoherent FSK modulation} & (5) \\
 (E_b/N_0)_{ac} - (E_b/N_0)_{er} &= \text{link margin in dB (for BER = } 10^{-5}) & (6) \\
 (E_b/N_0)_{ac} - (E_b/N_0)_{er} &= \text{link margin in dB (for BER = } 10^{-6}) & (7)
 \end{aligned}$$

Table II - Numerical Values for Terms in Equations of Table I

$P_{\text{hub}} = \text{transmit power of hub} = 3 \text{ W}$
 $P_{\text{sat}} = \text{transmit power of satellite} = 5 \text{ W}$
 $P_{\text{rem}} = \text{transmit power of chemical remote sensor} = 3 \text{ W}$
 $G_{\text{hub}} = \text{antenna gain of hub} = 38.5 \text{ dB} = 7079.5$
 $G_{\text{sat}} = \text{antenna gain of LEO satellite} = 4.0 \text{ dB} = 2.5$
 $G_{\text{rem}} = \text{antenna gain of remote} = 3.0 \text{ dB} = 2.0$
 $R = \text{slant range} = 1803.2 \text{ km} = 1.803 \times 10^{-6} \text{ m}$
 $k = 1.38 \times 10^{-23}$
 $T_s = \text{system noise temperature at the receiving end of a link (either hub, satellite, or remote)}$
 $T_{\text{rem}} = 2510 \text{ K} = \text{noise temperature of a remote chemical sensor}$
 $T_{\text{sat}} = 550 \text{ K} = \text{noise temperature of a LEO satellite}$
 $T_{\text{hub}} = 300 \text{ K} = \text{noise temperature of the hub}$
 $R_d = \text{data rate} = 518 \text{ bps}$ for ion mobility spectroscopy
 $R_c = \text{data rate} = 1810 \text{ bps}$ for SAW chemical sensor
 $\lambda_{\text{hub}} = \text{wavelength of transmission in meters}$
 $\text{fade} = \text{degrading effect of multipath fading or other fading on transmission} = 3.0 \text{ dB} = 2.0$
 $\text{BO} = \text{backoff} = \text{offset from peak power at satellite transponder to avoid nonlinear distortions}$
 $= 3.0 \text{ dB} = 2.0$

Table II - Link Margin Results

Sensor Type	Link Type	Link Margin (1.0 E-5 BER)	Link Margin (1.0 E-6 BER)
DMS	Return	17.70 dB	16.72 dB
DMS	Polling	11.53 dB	10.69 dB
SAW	Return	13.05 dB	12.97 dB
SAW	Polling	6.86 dB	6.02 dB