Performance Analysis of Link Rendezvous Protocol for Cognitive Radio Networks

Work-in Progress
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***Abstract*—A link rendezvous protocol is proposed in the context of first responder applications. These applications require protocols that can withstand the total loss of infrastructure, evolve autonomously, and scale to meet the capacity demands of a crisis. Our protocol does not rely on critical infrastructure. It is designed to be spectrally efficient and it minimizes the risk of interference to ongoing communications.**

We present an overall process which facilitates establishing and maintaining self-configuring networks based upon a service paradigm. We then present the link rendezvous process in detail. At the heart of this process is an attention signal composed of a carrier with carefully designed side tones. The parameters and performance metrics associated with this attention signal and link rendezvous protocol are discussed. The probabilities of false positives and negatives in the detection of this signal are analyzed numerically. Time to connect factors are also analyzed.

I. Introduction

Recent years have seen the untimely failure of first responder communication systems during disaster scenarios when they are most needed [1]. These systems have failed due to a loss of critical infrastructure, incompatibility between the communication systems of responding agencies, inability to scale to meet the capacity demands of the crisis, and in some instances, difficulty in usability in the heat of the moment [2]. As many researchers have noted, software defined radio (SDR), cognitive radio (CR), and dynamic spectrum access (DSA) are technologies especially suited to overcoming these problems [3]–[5].

We envision a future communication system approach which seamlessly and securely establishes individual links and bootstraps entire networks without reliance on any fixed infrastructure. In disaster response scenarios, users desire to establish a network as soon as possible and to evolve that network as more communication assets are deployed to the scene. Self configuring networks are highly advantageous in these scenarios. Capacity is also a chief concern during crises. The system should, under the appropriate policies, harvest spectrum to build capacity. It should also discern which communication resources are available and utilize them appropriately. This should all be accomplished collaboratively within the network, and autonomously with regard to requiring resources outside the network.

Link rendezvous is a critical step in bootstrapping a network [6]. Since infrastructure is often lost or overwhelmed during a crisis, the link rendezvous should proceed unaided from any centralized coordination. Furthermore, it should exhibit a high probability of rendezvous, provided communication resources are within radio range. Finally, it should minimize the risk of interference with ongoing communications, as normal collaborative spectrum sensing is not practically accomplished until an initial link is established.

We propose and analyze a link rendezvous protocol which meets these requirements. At the core is an attention signal for which monitoring nodes continuously scan and connecting nodes emit. The decision that the signal is present or not is formed in the frequency domain, allowing receiving nodes to scan a wide range of frequencies at once, avoiding the need for an *a priori* determined signaling channel.

The remainder of this paper is organized as follows. Related work is presented in Section II. Section III presents the proposed link rendezvous protocol in detail. Section IV explores the various protocol parameters that can be tuned, the performance metrics that ultimately determine the efficacy of this approach, and numerical results. We conclude in Section V.

II. Related Work

Polson [6] identifies two main approaches toward link rendezvous. The first assumes some infrastructure which transmits a beacon encoded with time and frequency rendezvous information. Cognitive radios request a time-frequency slot for a specified network and provide location and power information. The infrastructure server recommends a frequency and schedules a time for the CR to check back in. The server has an omniscient view of all CRs in the area and can globally optimize its decisions.

As previously noted, infrastructure is not always appropriate. Polson also describes two versions of an unaided approach. Both rely on the calling node emitting a probe signal on a selection of available frequencies. Receiving nodes listen on the set of frequencies that they determine are available. When the original probe waveform is detected, the receiving node transmits its own probe-acknowledgement waveform, signalling its readiness to establish a connection. Once connected, the nodes exchange information which expands their knowledge of the spectral environment.

Balachandran and Kang propose a set of protocols assuming slotted frequency hopping sequences [7]. They present the probability of achieving a link within a given time for the various protocols. These protocols rely upon timing synchronization through a standard such as GPS or acquisition from a neighboring node.

Han, Wang and Li describe a link establishment process centered around a base station and multiple mobile stations [8]. Their system relies on an interleaved OFDM-based transform domain communication system for establishing the first connection. This spread spectrum technique minimizes the potential for interference with ongoing communications.

Holland, et. al. propose a universal dedicated channel to communicate spectrum resource availability and usage [9]. Each radio periodically broadcasts information about the resources used by the communications it receives. Sutton, et. al. recently described a technique which relies on cyclic signatures embedded in OFDM signals to trigger rendezvous in low signal to noise applications [10].

We first presented our proposed link rendezvous protocol in our previous work [11] where we explored the detection limits by prototyping key parts of it in the open source project GNU Radio [12].

III. Link Rendezvous Protocol

While the protocol is described in [11], a brief summary is provided here. In this rendezvous protocol, the link requestor emits an attention signal composed of a specified set of tones. It transmits this signal on a limited number of frequencies it has determined are vacant and available for use. The attention signal is described by equation (1).

$$s = A_o \cos(\omega_c t) \sum_{j=1}^{J} A_j \cos((\omega_c + \omega_j)t) \tag{1}$$

where j represents the j^{th} modulated tone and typically $\omega_c >> \omega_j$.

Nodes on standby continuously monitor the spectrum for this pattern. SDR technology allows the radio to scan many channels at once. An entire band can be sampled, based upon the performance of the A/D converter and system processing speed. A Fast Fourier Transform (FFT) is performed on the resulting sample stream. A feature detection algorithm searches for the well defined pattern given in equation (1). The receiving node collects all of the attention signal occurrences it finds within its scanning range and chooses which frequency to use in response. It then transmits a similar but distinct pattern of its own on the chosen frequency.

After the initial transmission, the calling node switches to a listen mode. It scans all of the frequencies on which it originally transmitted, looking for the reply pattern of sidebands. In dense RF environments, it might receive more than one reply. The calling node chooses the final frequency on which to connect from the set of responses. This decision may be based upon signal strength or other ranking. The node is finally ready to establish a connection. It broadcasts a connection request code using some reasonably lowest common denominator RF parameters on the chosen frequency.

After transmitting the attention reply signal, idle receivers enter a listen mode for a connection request. Upon detecting a connection request, the receiver transmits a connection response message directly to the originating node. This message is the first unicast message and can include information about the node such as the services it can provide and connection parameter preferences. The originating node chooses to which destination node to connect which finishes the rendezvous process. The hypothesis that leads to the use of an attention signal detected in the frequency domain is that the transmitter can secure the attention of a receiver with a minimal energy, bandwidth and duration. This is achieved primarily by an SDR's ability to monitor multiple channels simultaneously.

The decision statistics are ratiometric in nature and can be summarized as in equation (2).

$$H1 : \bigcap_{n=1}^{N} [A_n A_o - tol < S_n < A_n A_o + tol] \tag{2}$$

where $H1$ represents the hypothesis that an attention signal is present, A_n is the design relative amplitude for the n^{th} sidetone, tol is a tolerance to account for nonlinearities and some noise margin, S_n is the sidetone amplitude, N is the number of sidetones and A_o is the carrier amplitude. The alternate hypothesis, $H0$ is assumed when any one these conditions are not met and indicates that there is not an attention signal present.

IV. Performance Study

A. Protocol Parameters and Performance Metrics

A link rendezvous protocol should balance the desire to quickly and reliably establish a connection with the risk of interfering with ongoing, protected services. Secondary criteria include minimizing energy consumption, avoiding detection (in covert applications), and preventing unauthorized eavesdropping. There are a number of parameters in the attention signal protocol. The primary parameters are 1) output power, 2) number of side tones, 3) spacing of side tones, 4) relative amplitude of side tones, and 5) tone duration. The output power and to some extent, the tone duration are determined at the time of use, whereas the remaining parameters must be determined *a priori* as their values must be encoded in the detection algorithm.

In the context of this link rendezvous protocol, there are a number of important performance metrics.

1) Probability of Detection In Time: The purpose of the attention signal is to facilitate the initiation of a first communication link. The speed at which this occurs is a prime consideration. This can be specified in terms of maximizing the probability of achieving a connection within a specified time or alternatively, minimizing the mean connection time.

2) Probability of Unintentional Interference: Some of the same factors which improve connection time worsen the probability of causing unintentional interference. In particular, transmitting longer and with more power increases the potential of causing interference.

3) Energy Required to Establish a Link: The energy required to establish a link is a critical parameter in battery powered applications. It would be ideal to emit the attention signal and reply at the minimal energy required to establish a connection without iteration. This would require *a priori* knowledge of the channel characteristics, in particular the distance from the transmitter to the receiver, and the receiver performance.

4) Energy Required During Standby: It is integral to this method that nodes not cooperating in an ongoing communication, listen for the attention signal and participate in the rendezvous process if they are able. This process consumes energy in that the receiver and processor must operate.

5) Probability of False Positives: A false positive occurs when the receiving node concludes that there is an attention signal present, when in reality, there is none. One way this can happen is if a signal has the same frequency domain characteristics at the carrier and offset frequencies as the attention signal. While it is difficult to analyze this in general, one could examine the characteristics of common signals in the particular band of interest. One would then logically design the attention signal to produce radically different characteristics.

A false positive entirely due to noise can be analyzed in a straightforward manner. In this case, noise at a potential carrier location produces a certain measured signal level. If the noise at the various offset locations produce a measured signal level within all of the side tone tolerance windows, the algorithm will conclude a false positive. An excess of false positives will clutter the spectrum due to unnecessary transmissions of the reply signal, drain the energy resources of the node, and increase the probability of unintentional interference with ongoing transmissions.

6) Probability of False Negatives: A false negative occurs when the receiving node concludes that there is no attention signal present, when in reality, there is one. The predominant cause is additive noise causing the relative amplitudes between the carrier and side tones to slip out of the tolerance window. This could also be caused by a deterministic signal adding to the attention signal to push the measured levels out of the tolerance window.

Excessive false negatives increase the time to establish a link because the sender will need to repeat the attention signal if no nodes respond. Unintentional interference can result, because the originating node will increase its power or tone duration in order to attempt to reach a node. This also increases the energy required to establish a link.

B. Numerical Results

We now evaluate analytically, the probabilities of false negative and positive detections and the time to connect.

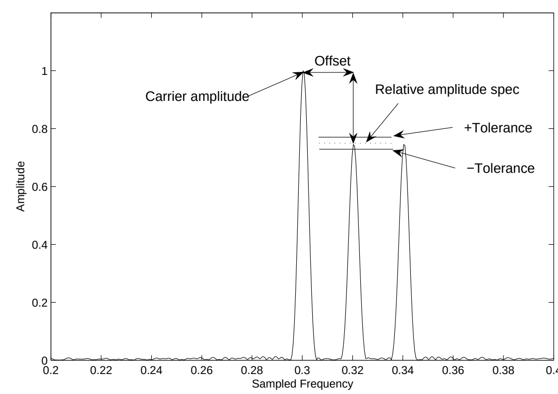

Fig. 1. Attention signal detection characteristics

1) False Detections: The probabilities of a false negative or positive are useful indicators of the overall effectiveness of this approach. These probabilities can be calculated based upon the relative amplitude between carrier and side tone(s), the number of side tones, the size of the tolerance window, the signal to noise ratio, and the signal duration. Fig.1 illustrates the formulation of the problem. Because noise exists in all practical radio channels, there is a finite probability that the system will misinterpret the noise as the presence of a signal or miss the presence of a signal, corrupted by noise. As previously discussed, this determines the required attention signal transmission parameters such as output power, number of side tones, and spacing of side tones. Minimizing the probabilities of false positives and false negatives tend to increase spectrum occupancy of the attention signal. We should therefore choose these transmission parameters carefully in order to maximize spectral efficiency.

Both the carrier and each side tone are independently affected by noise, assumed to be additive white gaussian noise (AWGN) in this analysis. The decisions are made after a magnitude operation; therefore, the gaussian distribution is transformed to a central chi-square distribution with 1 degree of freedom (where the noise is assumed to be real). The probability density function is given in equation (3).

$$f(y) = \frac{1}{\sqrt{2\pi y}\sigma_n} e^{-y/2\sigma_n^2} \tag{3}$$

where σ_n is the noise variance.

The decision is found by measuring the amplitude of the carrier, then measuring the amplitude at the side tone frequencies. If the relative amplitude between the side tone and the carrier is within the tolerance window, the decision is true, indicating that an attention signal is present. A false positive occurs when the noise at a carrier frequency is higher than the noise at all of the side tone frequencies by an amount equivalent to the specified relative amplitudes. A false negative occurs when the noise affects the carrier and the side tones in such a way that one or more of the signals is pushed out of the tolerance window.

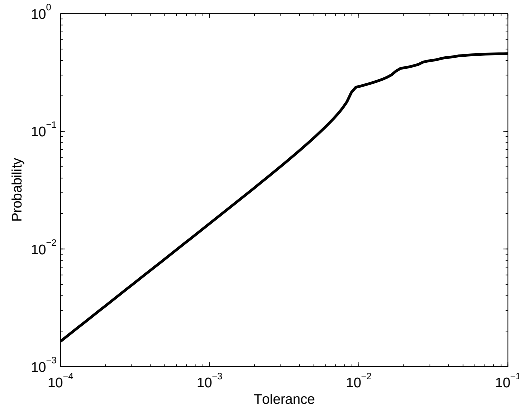

Fig. 2. Probability of false positive versus tolerance window ($\sigma_n = 0.1, A_o = 1.0, A_1 = 0.9$)

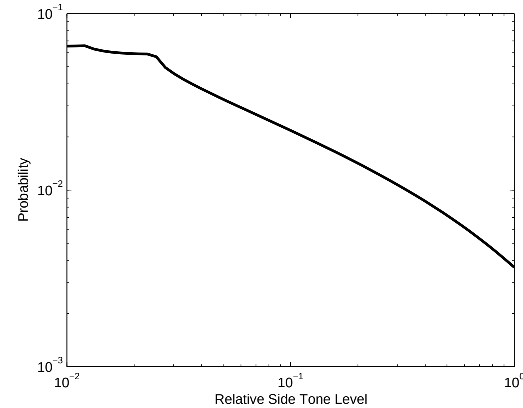

Fig. 3. Probability of false positive versus relative amplitude specification ($tol = 0.00025, \sigma_n = 0.1, A_0 = 1.0$)

The probability that the side tone amplitude is within the tolerance is conditioned upon the measured carrier amplitude. The conditional probability that the side tone is within the tolerance is found by integrating the noise probability distribution function through the tolerance window. This is illustrated for one side tone in equation (4).

$$P(fp|Pc) = \int_{-tol}^{+tol} f(y)\,dy \tag{4}$$

where $P(fp|Pc)$ is the probability of a false positive (fp) given a measured carrier amplitude (Pc), and tol is the tolerance used for the decision.

The total probability is found by multiplying the conditional probability by the probability of measuring that particular carrier amplitude and integrating the product from zero to infinity. This is described by equation (5). For more than one side tone, the probability decreases as in equation (2).

$$P(fp) = \int_{0}^{\infty} P(fp|Pc)p_c(x)\,dx \tag{5}$$

where $p_c(x)$ is the probability density function for the noise at the carrier location.

2) False Positive: of false positive as a function of the tolerance window is presented in Fig.2. Finally, the false positive probability versus relative amplitude specification is shown in Fig.3.

As expected, the probability of a false positive increases with a larger tolerance window. The probability is quite high overall, considering that the rate of false positives will be scaled by the number of analysis points in the FFT. Although it will decrease with additional side tones, it is clear that some thresholding will be required. In other words, the algorithm should only search for side tones when the energy in the carrier bin exceeds the quiescent noise floor of the system by a certain amount. This will reduce the range of detection, increasing the number of false negatives.

Keeping the side tone amplitude comparable to the carrier reduces the probability of a false positive. There is a knee in the curve near where the side tone amplitude approaches the noise level.

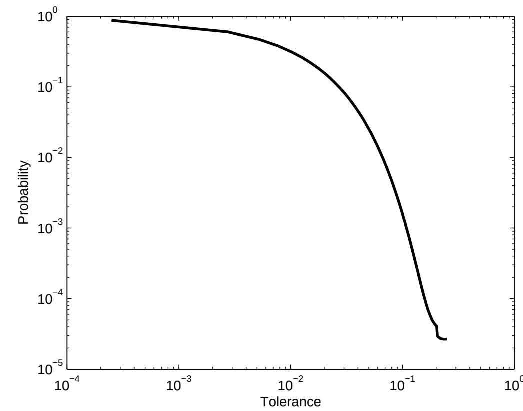

Fig. 4. Probability of false negative versus tolerance window ($\sigma_n = 0.1, A_0 = 1.0, A_1 = 0.3$)

3) False Negative: The possibility that additive noise at either the carrier location or one of the side tone locations causes the measured relative amplitude to push out of tolerance is termed a false negative. This is particularly sensitive to the tolerance window. As indicated in Fig.4, a very small tolerance window will produce greater rates of false negatives. The behavior at the largest tolerance window arises due to the window being nearly as large as the side tone level. The range of reasonable tolerance windows with respect to false negatives does not significantly overlap with that for minimizing false positives. Without modification, this would render this method ineffective. Thresholding the carrier measurement will prevent many of the false positives, allowing a choice of tolerance values that will provide for a reasonable false negative rate.

4) Time to Connect: The time to establish a connection is a function of the computations required to detect the attention signal and the probability that the receiver will be listening at the right time and band location. The calculations required to detect an attention signal are the FFT and a type of correlation.

The FFT time is proportional to $Nlog_2(N)$, where N is the number of points in an analysis frame. Especially for real data, very efficient implementations of the FFT algorithm exist. This efficiency factor will be represented by K. The correlation requires M multiplications for each of the N points, where M is the number of side tones. If one assumes that the computation time is dominated by the multiplications, then the computation time is related to equation (6).

$$T_a \propto KNlog_2(N) + NM \tag{6}$$

where T_a is the computation time to process the attention signal.

A radio node may choose to not monitor continuously in order to conserve energy or devote its resources to other requirements. This is represented by a duty factor, DF, where the time spent listening is assumed to be periodic. DF is then defined as the time spent listening divided by the total period. The listening time is assumed to be significantly greater than the normal time duration of the attention signal. Since the sending and receiving nodes are acting independently before a connection is established, the probability that the node will be listening when the sending node is transmitting is uniformly distributed.

Due to hardware limitations in sampling and processing speed, the listening node may only be able to monitor a portion of the operating band at a time. The maximum bandwidth is $1/2T_s$, where T_s is the sampling rate. If the operating bandwidth is BW_o, and the listening node sequentially processes each band, then the portion of a period that the listening node is monitoring the particular band in which the sender is transmitting is $1/(2T_sBW_o)$. This analysis assumes that heterodyne or similar techniques are used to select a particular band and sample it optimally.

The sampling rate and the number of points determine the frequency bin spacing at $\Delta f = 1/NT_s$, constraining N, since T_s is normally set by the choice of hardware. These parameters must be chosen in order to yield a sampled frequency bin spacing appropriate for the specified side tone spacing.

The sending node needs to listen for a attention signal response; however, it knows *a priori* on which frequency bins to listen. Let N_a equal the number of attention signals sent. The processing time in this case is given by equation (7).

$$T_r \propto KNlog_2(N) + MN_a \tag{7}$$

These issues combine to provide an average time to connect as specified in equation 8.

$$T_c \propto \frac{T_a 2T_s BW_o}{DF} + T_r \tag{8}$$

High values for the probability of false negatives will increase this time accordingly. Additional factors not considered here are the density of listening units within range and the iterations that are required when no units are within range, given a particular effective radiated power.

V. Conclusions

A strategy for link rendezvous has been presented which avoids a dedicated signalling channel, only requiring radios to operate within a common band. The concept minimizes unintentional interference during the rendezvous process by using a very short duration, narrow bandwidth, low power attention signal. The responding nodes begin coordinating the spectrum sensing by responding to the attention signal on a set of frequencies which it interprets as being clear. A number of performance metrics determine the overall utility of this process. The probabilities of a false positive versus side tone relative amplitude and tolerance window were calculated along with the false negative probability versus tolerance window size. It was found that thresholding to avoid processing signals below the system noise floor is necessary to achieve reasonable false positive probabilities. Finally, the factors involved in determining the mean connection time are derived.

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