xG TECHNOLOGY, INC.

WHITE PAPER

xMax Cognitive Radio System
Interference Mitigation Overview

1. INTRODUCTION

In recent years, there has been an exponential increase in the use of personal wireless communication devices such as laptops, smart phones and tablets. This in turn has sparked a growing appetite for bandwidth-heavy data and applications. For the mobile industry, this has resulted in a critical need to maintain reliable communications and ever-increasing capacity for subscribers against the backdrop of crowded spectrum.

As more users share the constrained airwaves used by today's data networks, they not only use more bandwidth, but they also increase the overall interference level in the network. To operate in these types of conditions, multiple solutions have been proposed. A traditional solution has been to carefully coordinate access by allocating resources (channels, resource blocks, etc.) in a manner that avoids interference.

The coordination of airwaves is often done using centralized control built into network infrastructure through complex protocols. However, when large numbers of users are sharing limited spectral resources, the traditional spectrum sharing methods may not be efficient. One indication of this is that the FCC has determined that 70% of the allocated spectrum may be sitting idle.

Another problem occurs when large numbers of devices communicate and send only small amounts of information. In this scenario, traditional protocols use an increasing portion of the spectral resources for control plane traffic. The projected explosion in the number of interconnected devices on the horizon, such as wearables, connected cars, smart appliances and entertainment systems will only exacerbate the problem. In this new reality of M2M and the Internet of Things, the protocols used to manage airwaves in the past do not represent the most effective approach.

One proposed solution to these challenges is to use cognitive radios (CR). Traditional cognitive radios have typically relied on sensing and dynamic spectrum access (DSA) to move away from channels with interference. This technique assumes that channels without interference are available, which is often not the case. Therefore, increasing network performance in cognitive networks requires a sophisticated, highly adaptive cognitive engine designed to work in "gray spaces" (frequencies with high levels of interference), and, in some cases, "black spaces" (frequencies undergoing intentional jamming).

In this paper, we introduce a new type of cognitive radio that uses interference mitigation, which leads to a significant increase in cognitive system performance.

2. OVERVIEW OF INTERFERENCE IN THE 900MHZ ISM BAND

To illustrate the challenges involved in sharing spectrum, the 900MHz unlicensed band is used as an example. This band is extensively used by various devices, from telemetry and video links, to cordless phones and wireless baby monitors. To comply with FCC part15 rules in the U.S., the minimum bandwidth, power spectral density and transmit power are strictly limited. The minimum bandwidth is 500 kHz and maximum radiated output power is 36dBm EIRP.

Common interferers in the band include cordless phones that use frequency-hopping spread spectrum modulation. Another common type of transmission used by fixed broadband systems is wideband Frequency Shift Keying (FSK) or Orthogonal Frequency Division Multiplexing (OFDM). These types of systems often occupy the entire 902-928MHz band.

Many of these systems are good for their intended use. Cordless phones operate well for voice and garage door openers operate using a very low cost hardware implementation. The issue is that large portions of the band are not used or are rarely used. For example, a garage door opener is typically used only a few times a day.

To operate a mobile broadband data network in the presence of these systems, multiple methods to mitigate the interference are required.

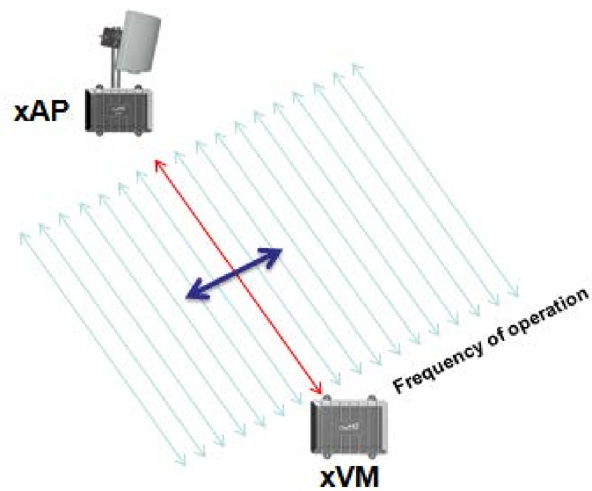
3. THE xMAX RADIO SYSTEM

In order to create scalable network designs, the xMax network contains the typical components of a radio system, i.e., Access Points (xAP) and Vehicular Modems (xVM). Access Points are used as infrastructure elements to create a coverage area, while Vehicular Modems are mobile terminals. Vehicular modems can roam in the network while maintaining a seamless IP connection so that user applications experience full mobility and motion at highway speeds.

While the xMax network delivers a traditional cellular network-type of user experience, the architecture and operation of an xMax network are somewhat different from traditional networks. One key aspect of the network design is that it avoids centralized control. The system does use some degree of coordination; for example, radio channels and time slots are used in a similar fashion as in traditional wireless networks. The coordination between devices, however, is fully distributed.

Each access point only serves devices that are associated with it. When a connected mobile station requires data transfer capacity, it accesses an xAP that it is associated with and requests capacity that is granted by the xAP. The grant consists of spectral and time resource, i.e., a channel and time slot (or time slots). Each xAP controls resources for its local channel, and there is no coordination between access points except for xAP channel allocation. Even coordination of mobile devices that are associated is very limited. The xAP provides data transfer capacity and coordination for channel access.

In an xMax network, the mobile terminal independently makes decisions on what access point to associate with. To select the best access point, the mobile device continuously scans for beacon signals from multiple access points. The beacon signals are transmitted so that the device can scan up to three channels every 20ms. When operational, the mobile device maintains a list of potential access points.



Interference mitigation technology is used at all times to process received signals. The measurement of beacon signals using the technology allows the receiver to decode data that would be lost in a traditional design. For this reason, the network appears to operate like a traditional cellular network, while in reality the spectrum is shared by multiple devices, including xMax and non-xMax devices.

4. THE xMAX COGNITIVE ENGINE

From both ends of the xMax network (the xAP and the xVM), the system components are continually looking at the RF operating conditions and system performance. Decisions to hand off to better system channels are made based on interference, lack of responses, dropped IP packets and missed acknowledgements.

The xMax system assigns radio channels to access points if configured to do so. The access points in the network measure received signal strength for uplink in channels that are defined as being allowed for communication. Each device independently chooses a channel that is the best for communication, based on interference criteria.

Each mobile device maintains a list of channel measurements, referred to as a Preferred Channel List (PCL). The PCL contains information including noise floor, channel statistics, SINR, and MAC addresses of preferred xAPs.

The dynamic channel selection is a function of both uplink and downlink channel qualities. For the access point DSA, the xAP looks for interference on the channel of operation and determines if it exceeds a predetermined threshold that would degrade system performance. If this threshold is exceeded, it generates a handoff trigger, in which the access point instructs the xVM to switch to another channel from the available frequencies in the PCL.

For the xVM DSA, the xVM makes handoff trigger decisions based on its perception of the uplink signal quality. The purpose of these triggers is to combat asymmetric channels where the downlink to the xVM is different from the uplink.

The following are the three handoff triggers considered:

No Response: If the xVM does not receive a successful response from the xAP after a set limit of retries, the xVM will use this as a handoff trigger to look for another channel from the PCL and switch to this channel.

Data Burst Loss: The xVM determines if data bursts are lost during transmissions. The total number of data bursts attempted and dropped are accumulated over a period of time. If the percentage of data burst loss is greater than a set limit, a handoff is triggered. The xVM will then look for another channel from the PCL and switch to that channel.

Missed Acknowledge counts: The xVM relies on constant feedback from the xAP regarding the success of transmitted data bursts. An ACK is a positive acknowledgement of the reception of a burst while a NACK is an explicit indication from the xAP that the expected burst of data was not received. The number of ACKS and NACKS are collected over a period of time, and the percentage of NACKS over ACKS is calculated. A predetermined handoff threshold is set and if this threshold is exceeded, a decision is made to initiate a handoff to a new channel. Again, the xVM will this look for another channel from the PCL and switch to that channel.

5. xMAX INTERFERENCE MITIGATION

In a deployed network, multiple access points (or base stations) may face a situation where the same RF channel is used by access points that interfere.

Traditional cellular systems use different approaches to address this, including channel or resource block allocation and power control. Typically, interference is reduced by using some type of coordination — but at the expense of overall system capacity and efficiency. For example, one method, fractional power control, avoids interference by reducing power for devices that are far away from the access point, i.e., closer to other access points. While this is effective, it may not deliver the capacity that is possible if all the radios were interference resistant.

The xMax system is able to effectively mitigate interference in a way that enhances system capacity and performance over traditional approaches. The interference mitigation technology used in xMax consists of a multi-antenna receiver, long time domain interleaving, forward error correction and ARQ. The xMax receiver consists of four antennas and RF receivers, and signal processing that combines the antenna signals. The system uses two types of receivers – a maximal ratio receiver and a receiver that mitigates interference.

xMax interference mitigation is done in both frequency and time domain. The OFDM signal consists of a large number of subcarriers. The channel coherence bandwidth is expected to be larger than single subcarrier bandwidth. This makes it possible to compute a channel estimate for each subcarrier using other subcarriers above and below in frequency. Additionally, the channel coherence time is expected to be larger than the RF burst time so that computed estimates can be interpolated in time domain to cover each RF burst. To make these operations effective, the xMax physical layer waveform includes channel sounding bursts that repeat at 800 microsecond intervals.

The receiver computes overlapping channel estimates using both MRC and LMS algorithms. Because of this, when the four antenna signals are combined based on the computed estimates, interference is minimized.

One of the adaptive antenna technologies available to the xMax cognitive engine is a subspace projection receiver. The receiver's LMS-based algorithm uses multiple dimensions of a receive signal from a MIMO antenna to orthogonalize the interference to the desired signal. The performance of the algorithm depends on many factors, including the number of antenna elements, element spacing and correlation. The idea of the algorithm is to compute a projection from multi-dimensional signals so that Signal to Noise Ratio (SNR) is maximized.

The following image shows how subspace projection operates. It illustrates a 3-dimensional vector "a" projected on the 2-dimensional signal subspace "S". The point "P" is chosen so that "v" and "e" are orthogonal, where "e" is error signal, i.e. interference.

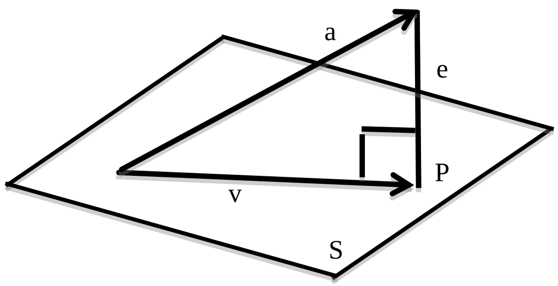


Figure 1. Projection method

To assess the performance of the system both simulations and field tests are used. The following image shows the normalized throughput versus narrowband interference level for coded 16QAM, with non-ideal synchronization and channel estimation, for various channel fading profiles. The field test performance of the system matches the performance very accurately up to point where timing and frequency synchronization is lost.

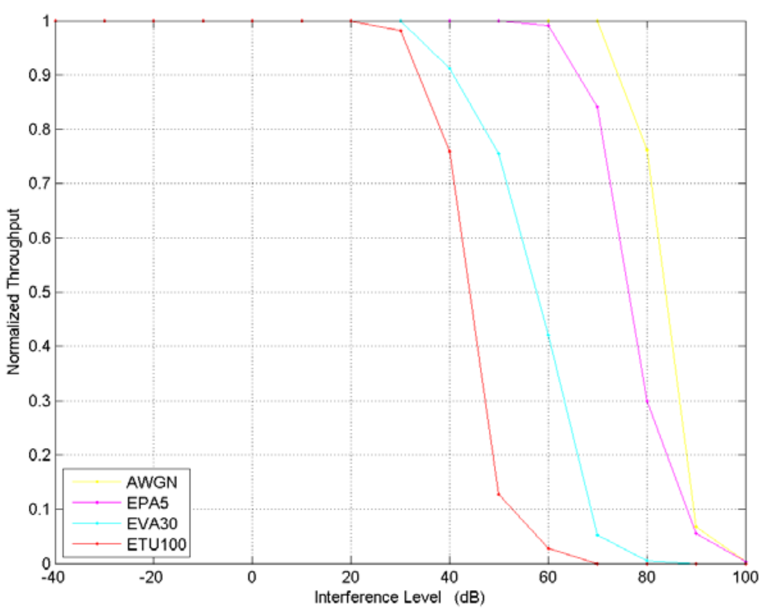


Figure 2. Normalized throughput vs. interference

Note: The channel profiles shown in the graph represent the following signal noise models that are used to mimic the effect of random processes occurring in nature:
***AWGN** - Additive White Gaussian Noise*
***EPA5** - Extended Pedestrian A 5 model (pedestrians)*
***EVA30** - Extended Vehicular A 30 model (in-vehicle users)*
***ETU100** - Extended Typical Urban 100 model (high-speed users on highways)*

Based on field tests and simulations, the interference mitigation allows xMax to operate beyond -10dB SINR (Signal to Interference + Noise Ratio) values, i.e. the co-channel interfering signal power can be more than 10 times the power of the desired signal. Beyond these conditions, it is challenging to maintain correct receiver timing and frequency.

The time synchronization uses pilot signals to do a coarse time tracking. The system expects to find at minimum one correctly received beacon burst every two seconds or the timing synchronization is lost and channel acquisition is started. The fine timing and frequency synchronization uses spread spectrum technology, i.e. a random sequences and correlation to compute the timing and phase of reference signals.

SUMMARY

The traditional approach to dealing with interference challenges to wireless systems has been dynamic spectrum access, which is essentially an attempt to avoid interference. By contrast, xG Technology is the only company to utilize an innovative, layered cognitive radio approach which incorporates dynamic spectrum access, but in which intelligent and active interference mitigation plays a dominant role. It is an approach that greatly increases the carrying capacity and performance of both existing private and unlicensed spectrum, and can deliver key benefits to wireless planners in a number of sectors that deal with limited spectrum resources, such as government agencies, public safety and emergency management.

ABOUT XG TECHNOLOGY

Founded in 2002, xG Technology_has created a broad portfolio of intellectual property that makes wireless networks more intelligent, accessible, affordable and reliable. The company is the developer of xMax, a patented all-IP cognitive radio network system that enables secure, robust mobile broadband communications for private, consumer and government networks. xMax solves the crisis facing the wireless industry caused by data-hungry devices and applications that are straining network capacity. It eliminates the need to acquire scarce and expensive licensed spectrum, thus lowering the total cost of ownership for wireless broadband access.

The xMax system delivers always-available voice, video and data services to both fixed and mobile users, and is interoperable with existing cellular and dedicated networks without being dependent on them. xMax incorporates advanced optimizing technologies that include spectrum sharing, interference mitigation, multiple-input multiple-output (MIMO) and software defined radio (SDR). These and other technologies make xMax ideal for wide area, as well as rapid emergency communication deployment in unpredictable environments and during fluid situations. xG offers solutions for numerous industries worldwide, including emergency response and public safety, military, urban and rural wireless broadband, utilities, and critical infrastructure.

Based in Sarasota, Florida, xG has over 50 U.S. and over 100 international patents and pending patent applications. xG is a publicly traded company listed on the NASDAQ Capital Market where xG common stock is traded under the symbol XGTI. For information, please visit www.xgtechnology.com.