THE THREE 'A'S OF COMMUNICATIONS – RADAR SPECTRUM SHARING

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ABSTRACT

The continuing need for Radio Frequency spectrum has led to an increasing interest in spectrum sharing between radar and communications systems. This paper presents a taxonomy of the three classes of radar-communications spectrum sharing techniques; Avoid & Mitigate, Accept and Amalgamate – the three 'A's. The various schemes that have been proposed and/or are under development are mapped into the three classes. The three 'A's formulation is used to discuss the current status of radar-communications spectrum sharing, potential directions for future research, and provide context for radar-communications spectrum sharing business cases. It is shown that there are different business cases associated with each of the three 'A's.

1. INTRODUCTION

The continuing need for Radio Frequency spectrum has led to an increasing interest in spectrum sharing between radar and communications systems. Sharing between radar and WiFi access points using Dynamic Frequency Selection (DFS) [1] has been attempted in C-band / Unlicensed National Information Infrastructure (UNII) band [2], and is proposed for S-Band [3]. Meanwhile, DARPA's SSPARC program is developing new communications-radar spectrum sharing technologies [4]. This paper presents a taxonomy of the three classes of radar-communications spectrum sharing techniques; Avoid & Mitigate, Accept, and Amalgamate – the three 'A's (Figure 1).

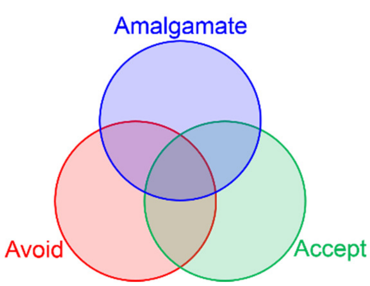

Fig. 1. A Venn diagram depicting the three classes of radar-communications spectrum sharing techniques.

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This paper is organized as follows. Sections 2, 3 and 4 describe each of the three classes of radar-communications spectrum sharing techniques. Section 5 discusses the business cases associated with each of the three 'A's, and finally the three 'A's formulation is used to discuss the status of current research and future directions for radar-communications spectrum sharing.

2. AVOID & MITIGATE

The Avoid & Mitigate (A&M) approach that forms the basis of most radar-communications spectrum sharing techniques is also the basis for Cognitive Radio systems that "automatically detect available channels in wireless spectrum, then accordingly changes transmission or reception parameters to allow more concurrent wireless communications in a given spectrum band at one location" [5]. The broad class of techniques that come under A&M are depicted in Figure 2.

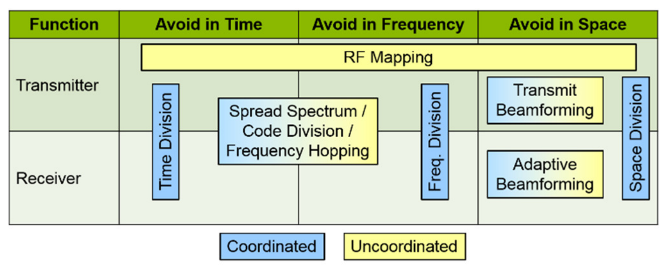

Fig. 2. Avoid & Mitigate encompasses a wide range of techniques that may be coordinated or uncoordinated between the radar and communications systems.

The range of techniques that are encompassed by the Avoid & Mitigate class may occur in the transmitter or receiver, may avoid or mitigate in time, frequency and space, and may or may not be coordinated between the transmitter and receiver. The DFS technique used for the UNII band is classed as the uncoordinated avoidance in frequency by the receiver. However, for a number of reasons the DFS approach did not result in an interference-free environment [12-14]. As a result much of the continued research in the Avoid & Mitigate class has been directed to coordination or coupling between the communications and radar to eliminate interference [15].

The Avoid & Mitigate class of approaches attempt to minimize the interference at the radar and/or communications receiver. Thus the metrics for such approaches assume that the interference is avoided and/or mitigated so that there negligible degradation in system performance (e.g. [15]). However, accepting larger amounts of interference may also be a legitimate radar-communications spectrum sharing approach, as is described below.

3. ACCEPT

3.1 Communications

Many communications systems accept co-channel interference as the price that is paid for spatial reuse of the spectrum. In communications the potential channel capacity is governed by Shannon's Theorem [6], which can be expressed in a bandwidth-normalized form as

$$Spectral\ Efficiency = \log_2(1 + SINR)\ b/s/Hz, \qquad (1)$$

where *SINR* represents the Signal to Interference Plus Noise Ratio. Thus giving up SINR in return for either bandwidth or time is a worthwhile trade for communications systems when the SINR is high. This is demonstrated in Figure 3, which shows that going from a 30 dB SINR to a 20 dB SINR while increasing the bandwidth 10-fold improves the data rate by a factor of 6.7.

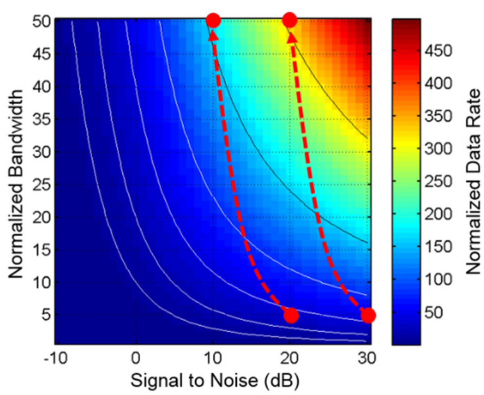

Fig. 3. Data Rate as a function of Signal to Noise Ratio and Bandwidth, demonstrating that bandwidth is more valuable than Signal to Noise Ratio.

Accepting co-channel interference in exchange for bandwidth allows better spatial re-use – i.e. a higher Area Spectral Efficiency (measured in b/s/Hz/m^2) [7]. This is exemplified by the practical operation of cellular communications systems and WiFi.

3.2 Radar

Radar's primary metric is probability of detection, which (to the first order[1]) is a function of the SINR and independent of bandwidth [8]. Figure 4 shows an example of how probability of detection varies with SNR and bandwidth. For the same 10x SINR / bandwidth trades indicated in Figure 3 for communications, there is always a degradation in radar performance. The degradation may be small if the SINR is sufficiently high, or significant reducing the probability of detection to near-zero if the SINR was only just high enough to obtain a probability of detection of 0.9.

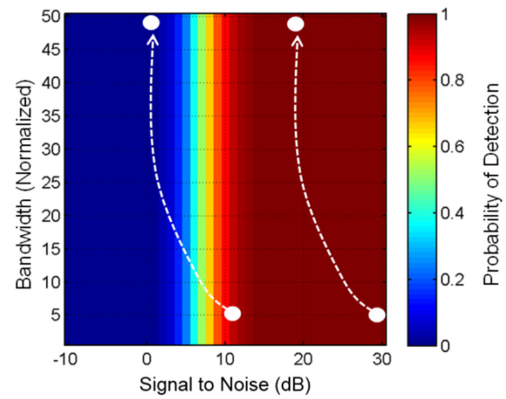

Fig. 4. Radar probability of detection is independent of bandwidth (to the first order). The detection threshold was chosen to provide a probability of false alarm of 10^{-6} [9]. The target's radar cross section follows the Swerling 0 model [9].

This illustrates a key difference between radar and communications. Radar probability of detection is essentially energy limited, whereas communications data rate is limited by the bandwidth and the logarithm of energy. Thus the acceptance of interference in exchange for bandwidth that enables better spatial reuse and hence a higher Area Spectral Efficiency for communications-communications spectrum sharing does not carry over into radar-communications spectrum sharing. However, this does not mean that the Accept paradigm for radar-communications spectrum sharing is infeasible, it is just different to the communications-communications scenario.

3.3 Example Interference Acceptance Scenario

Although the preceding discussion paints a bleak picture for radar-communications spectrum sharing through mutual acceptance of interference, there are in fact techniques that could be applied. Figure 5 below demonstrates an example scenario where radar and communications could coexist in the same spectrum. To restore the loss in the radar's sensitivity due to the interference generated by the communications, the radar generates more transmitter power. The radar still only transmits a small proportion of the time (~10% for modern solid state radar systems [10]). Since the communications system only observes interference about 10% of the time in short (<1ms) bursts, a Forward Error Correction scheme may be chosen to mitigate the losses. Recent testing has shown that the Forward Error

[1] To the extent that probability of detection depends upon suppressing the ground clutter, a minimal amount of bandwidth is needed for clutter suppression.

Correction schemes used in current Cellular Communications systems such as LTE can effectively deal with radar interference [11].

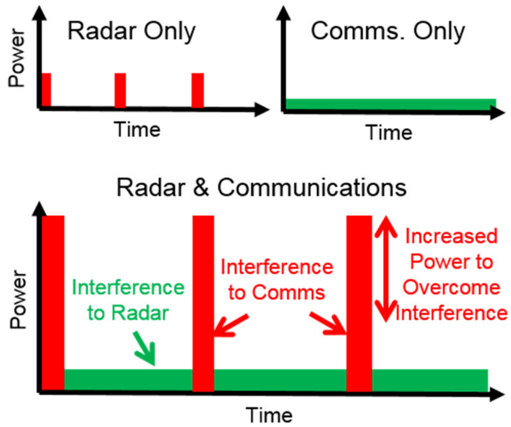

Fig. 5. The radar generates higher power to compensate for the interference from the communications. The communications system tunes the Forward Error Correction coding to mitigate the implusive radar interference.

Although it may seem inconsistent, building bigger, more-powerful radars is part of the solution-space for spectrum-sharing radar-communications systems that accept each-other's interference. The other key aspect of the solution space is likely to be coordination/feedback between the radar and communications systems to ensure that the interference level at the radar system remains 'acceptable'.

4. AMALGAMATE

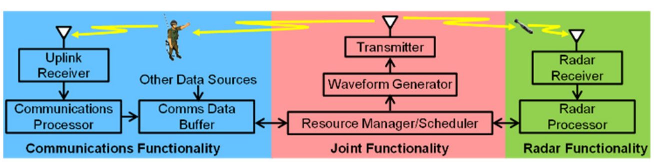

Fig. 6. Anatomy of an amalgamated radar-communications spectrum sharing system.

Amalgamating the radar and communications functionality into a single system results in a single transmitter that blends the radar and communications waveforms. There have been a number of examples of such systems that have been described [16-23], often as a result of the desire to add communications to an existing radar platform rather than the need to share a spectrum.

Fig. 7.

Figure 6 depicts the anatomy of an example amalgamated communications-radar system. The transmit chain (with the associated scheduling) is the only joint aspect of the system. The communications and radar receiver chains both interact with the transmitter, but are independent of each other. Amalgamated radar-communications spectrum sharing may be interpreted as a deliberate version of the use of communications signals of opportunity by Passive Coherent Location (PCL) radar systems [24]. While PCL systems must make do with the properties of the available signals of opportunity, amalgamated communications – radar systems can adjust the waveforms' properties to better optimize / balance both radar and communications performance. Table 1 below describes how some aspects of the waveform affect radar and communications.

TABLE I. HOW DIFFERENT WAVEFORM ATTRIBUTES AFFECT RADAR AND COMMUNICATIONS PERFORMANCE.

Waveform Aspect	Radar	Communications
Amplitude Modulation	Reduced SNR	Higher Data Rate
High Duty Factor	Reduced Coverage	Higher Data Rate
Multi Carrier	Reduced SNR	Lower Complexity
MIMO	Better Resolution	Higher Data Rate

A key issue embedded in the results in Table 1 is that radars prefer constant envelope waveforms, thereby maximizing the amount of energy used to illuminate targets. This contrasts with communication systems that accept waveforms with significant peak-to-average power ratios as an aid to getting higher data rates (e.g. QAM modulation) and/or simpler receivers (e.g. multi-carrier modulation such as OFDM) [25]. Another area of contention between radar and communications is that of duty factor. A high power radar is typically unable to receive while transmitting, so a transmit duty factor of around 10% is preferred [8]. A frequency-division duplex communications system is most efficient while transmitting 100% of a the time and a time division duplex system around 50% of the time (depending upon the proportion of data being uploaded vs downloaded).

However, there are aspects of the waveform that can be mutually beneficial. One example is Multiple-Input-Multiple-Output (MIMO) techniques that both improve the resolution of radar systems [26] and the data rate of communications systems [27]. Simultaneous use of both on an amalgamated communications-radar system is being investigated as part of DARPA's SSPARC program [22].

5. BUSINESS CASES

To understand the business cases for the three 'A's, a taxonomy of the business models is necessary. At its simplest form the business models consist of radar and communications service providers that are independent of one another, providers who are coordinated with one another, and a joint provider.

Independent radar and communications service providers share the same spectrum and adhere to a common set of specifications that determine how their systems operate. However they are uncoupled - there is no real-time coordination between the radar and communications service providers. The use of the UNII band by DFS enabled wireless networks is an example of independent communications and radar service providers adhering to a common specification, namely that when the wireless networks detect the radar's presence they move to another frequency. One aspect of the independent business model is that the financial success of the communications provider is independent of the radar as long as the communications provider does not interfere with the radar.

Coordinated radar and communications service providers exchange information in 'real-time' to ensure the success of both services. DARPA's SSPARC program investigated both 'loosely coupled' and 'tightly coupled' communications and radar systems [4,15]. In this case the financial success of the communications provider is dependent upon the real-time coordination between the service providers. A higher degree of coordination has the potential for pushing larger amounts of data through the communications system while the radar suffers less interference.

A *joint* radar and communications service provider is a singleentity providing both the radar and communications services. This incentivizes the joint service provider to maximize synergies between the radar and communications systems.

While the taxonomy of service provided has been broken up into three discrete types, in reality there is a spectrum of service provider types that occupy the continuums between the independent and coordinated and coordinated and joint classes.

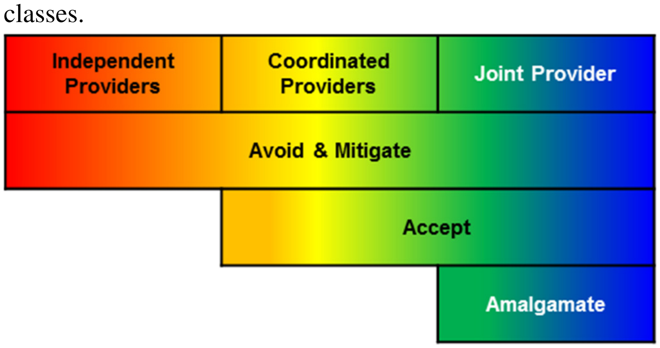

Fig. 8. The three 'As' span sucessively smaller parts of the service provider spectrum.

Figure 7 depicts how the three 'A's map into the provider taxonomy. The Avoid & Mitigate techniques can be applied across the provider spectrum. However, since some type of real-time coordination is required to keep the interference at acceptable levels, the Accept class is only applicable to coordinated and joint service providers. The Amalgamate techniques rely on common transmitters and waveforms for the radar and communications, hence they are only applicable to a joint service provider.

More insight can be attained by considering the real-world example of an Air Traffic Control radar sharing spectrum with a communications network. In the independent provider scenario, the communications network is designed not to interfere with the radar, requiring Avoid & Mitigate techniques. In the coordinated scenario, either Avoid & Mitigate, or Accept techniques may be used. In the joint scenario the radar also acts like a cellular tower distributing data to other wireless users while illuminating the target.

6. CURRENT RESEARCH AND FUTURE DIRECTIONS

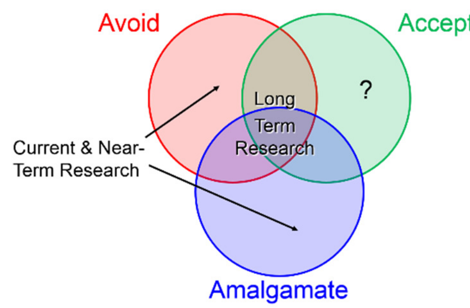

Fig. 9. Current radar-communications spectrum sharing research and future directions.

Figure 8 describes the current status of radar-communications spectrum sharing techniques. As a result of the DARPA SSPARC program most of the current research is in the Avoid & Mitigate [28-30] and Amalgamate areas [22, 23]. Interestingly, there is no ongoing work in the Accept area.

Once each of the three 'A's is understood, it is expected that research will then move to the intersections of the three 'A's. In particular, there are good reasons why practical systems with realistic business cases may live in the intersections. While 'pure' Avoid & Mitigate systems assume negligible interference between the radar and communications systems, it appears likely that the acceptance of some level of interference will provide an additional degree of freedom to the radar and communications system designers to produce practical systems with a reasonable business case. Future Amalgamated radar and communications systems may need to share spectrum with other systems necessitating their operation in the intersections with Avoid & Mitigate and Accept. The other communications system could even be communications uplink to the Amalgamated system. Such an uplink may be implemented more efficiently using Avoid & Mitigate techniques other than time or frequency division duplex along with some level of interference acceptance.

7. ACKNOWLEDGMENT

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