TOWARDS EFFICIENT SPECTRUM SHARING

Borivoje Nikolić

Berkeley Wireless Research Center
University of California,
Berkeley, CA 94720-1770

Abstract—One hundred years of spectrum sharing based on fixed frequency allocations have led to fracturing and poor utilization. Present methods of frequency allocation combined with a reliance on fixed infrastructure threaten to halt this growth. An additional consequence is the deployment of fundamentally less robust systems, prone to disruption in major disasters or overload. This paper outlines a vision of a system that, by enabling the secondary use of spectrum on an opportunistic basis and by establishing collaboration between the users, would enable a realization of ubiquitous, robust and agile wireless systems that are able to support further traffic growth and changing demands in traffic.

Abstract—Wireless communications, radio, transceivers, CMOS.

I. INTRODUCTION

Wireless communications are experiencing an explosive growth in the 21st century. Reliance on the mobile telephone for daily voice and data communication, and often for first contact in case of emergency, has become pervasive. Mobile telephones are widely deployed and are as commonly carried in our pockets or purses as wallets and house keys. Simultaneously, wireless LAN is presently included with all notebook computers and many portable computing, communications, and entertainment devices. Future wireless communications outline a growth path for better and more diverse coverage, higher data rates, and increased functionality over existing cellular, local area and personal area networks. All the new and growing applications require more bandwidth, and scarcity of the available spectrum jeopardizes this vision. On the other hand, wireless networks of today are prone to disruptions, particularly in cases of sudden surges in usage or major disasters.

This paper outlines a vision of a system that: (i) enables the secondary use of spectrum on an opportunistic basis and (ii) establishes collaboration between the terminals. The terminals in this system will operate in a very broad frequency spectrum with bands of operation that can be dynamically allocated. Such a system would be able to

reuse the frequency bands that the primary users are not using at a particular time and a particular location. The terminal will be able to migrate from infrastructure-supported operation to communication within a mesh network, using either centralized frequency allocation or intelligent and cooperative sensing of unutilized bands. The concept of secondary use of the spectrum, known as cognitive radio [1][2], in combination with advanced cooperation between system components is enabled by advances in fundamental communications and networking theory and continued improvements in integrated circuit technology. Because of its universal functionality, the same device can be used for many applications that otherwise require dedicated and expensive low-volume solutions. It is envisioned that a system like this would be able to support several modes of use:

- Commercial, high data rate, multi-mode communications.
- Public safety networks
- Communications in case of major disasters in true cognitive manner.

Commercial cellular networks benefit from large volumes of devices manufactured every year to bring the cost per user down. On the other hand, public safety radio communications are locked into separate frequency bands, which limit them to the use of low-volume and expensive solutions. The envisioned system would provide first responders with the large bandwidth necessary to transmit high data rate signals (such as video) from a large number of sources. Finally, in a case of a major disaster, where millions of people may get affected, with commercial communications disrupted, a system like this would provide expanding capacity needed for emergency communications. In this paper, a characteristic features that limit the growth of wireless communications today are discussed first, followed by a discussion about the cognitive collaborative wireless systems. The main technological limitations that need to be overcome are discussed next, and the paper is concluded with a brief summary.

Figure 1: A typical radio spectrum measured over 50 μ s using one-million-point FFT in downtown Berkeley [3].

II. CHARACTERISTICS OF WIRELESS COMMUNICATIONS TODAY

A striking characteristic of the ‘connected’ society is that a huge majority of the population now owns multi-standard, long-range, potentially location-aware radios in the form of mobile telephones. This device can have many uses beyond daily commercial communications; of particular interest are the uses by the public safety and by general population in a major disaster. The majority of people in need at a time of the disaster will have these devices with them; but they will not be able to utilize them, as the infrastructure they rely on to operate will not be useable.

Growth of commercial wireless communications and robustness of emergency services trace their challenges to the same set of obstacles:

- (i) Rigid principles of spectrum sharing;
- (ii) Traditional narrowband nature of radio transceivers, dictated by the underlying technology;
- (iii) Limited cooperation between different or similar devices, systems and standards;
- (iv) High dependence on wired infrastructure to operate wireless systems.

i) Rigid spectrum sharing. Spectrum is, by its very nature, a shared resource. The traditional approach of spectrum sharing is based on explicit spectrum division and licensing for a particular use. The use of spectrum as a shared resource is regulated by government agencies in each country (Federal Communications Commission, FCC, in the U.S.). Frequencies are assigned on a permanent basis and are very rarely re-allocated for different use. Within a licensed band, the spectrum is either explicitly divided among uses and users, or a restriction is imposed on the power transmitted by any individual user within a particular band. While these approaches have the advantage of conceptual simplicity and ease of enforcement, they do not scale with the demand for growing and evolving wireless communications.

One hundred years of spectrum sharing based on fixed frequency allocations have led to fracturing and poor utilization. Even when licensed, the spectrum is often not used; particularly when observed in a particular space and at

a specific time instant. Allocating a particular frequency band for the exclusive use of a single service wastes that frequency band whenever and wherever there happens to be insufficient demand for that service. Moreover, the use of the spectrum becomes inefficient whenever the technology delivering that service becomes antiquated.

The present way of spectrum sharing hampers the growth of wireless communications, because it is not scalable in terms of the number of simultaneous users and data rates:

- To enable higher data rates in wide-area networks operating with relatively narrow frequency bands, it is necessary to increase the number of base stations; which is not possible in most U.S. urban areas.
- It locks certain applications, like public safety, into particular bands where, because of the low volume of devices being manufactured, they cannot benefit from rapid technology advances available to high volume applications like mobile telephony.
- Centralized frequency control leads to infrastructure-based systems, which are fundamentally vulnerable to disruptions, particularly in the case of disasters and malicious attacks.
- The number of devices that can simultaneously operate is limited, which presents a major limitation in cases where many people need to communicate.

In Figure 1, a snapshot over 50 μ s at a sample rate of 20GS/s in downtown Berkeley, shows that the TV, FM radio, cellular and unlicensed bands are well utilized, while the spectrum usage at frequencies from 3–6 GHz is minimal [3]. The existing approach of allocation largely ignores two other degrees of freedom for sharing besides the frequency, the space and the time, and results in a spectrum scarcity in the presence of this spectrum abundance.

ii) Narrowband radio technology. All radio receivers since Armstrong’s can be viewed as methods of narrowband filtering that precedes a detector (or an analog-to-digital converter). This architecture matches well the traditional radio system specification of narrowband operation in a fixed frequency band. However, proliferation of modes and standards in modern communications has driven the demand for changes in radio architectures that can support multi-mode communications. Modern communications terminals need to implement WAN, LAN, PAN operation together

with positioning, while often supporting more than 20 different standards.

iii) Limited collaboration in communication systems. Rigid spectrum sharing, together with narrowband communications technology has contributed to the development of wireless systems with very little collaboration. Cooperation between the terminals within one system is often limited to establishing only peer-to-peer links, following a centralized allocation of resources by the access point or base station. Furthermore, cooperation between different wireless systems is often limited to coexistence in the same frequency band. This system concept greatly limits its capacity.

iv) Dependence on wired infrastructure. Wireless communication, by the nature of the signal transmission, promises high robustness to disruptions. However, this inherent robustness is limited by today's common practice of needing the wired infrastructure to achieve connectivity between wireless components. The heterogeneity of wireless systems in operation today spans a wide range of cell sizes, from peer-to-peer communications over local-area networks, to wide-area networks. Since they are all operated under different standards, there is no collaboration between these systems except the attempt to avoid causing each other interference.

III. COGNITIVE AND COLLABORATIVE RADIOS

A dramatic shift in wireless systems design occurs with the introduction of concepts of cognitive radios with collaboration between the terminals. The concept of a cognitive radio generally covers the secondary use of a spectrum allocated to a primary user on an opportunistic basis. In contrast to the ultra-wideband (UWB) transceiver, that presents the spectrum underlay by operating below the noise level, cognitive radio overlays the spectrum by operating in the 'white space' between the primary users. A spectrum of scenarios for operating cognitive radios can be envisioned, from the spectrum lease by primary users on a temporary basis, to unlicensed use of unused spectrum based on sensing the primary users. In many of these scenarios, it is envisioned that primary users, such as public safety systems will have the "right of way" and can deploy "lights and sirens" to request that non-critical systems yield spectrum.

The complementary concept of collaboration between the terminals within a cognitive system can dramatically improve the wireless system efficiency. Terminals in today's systems are generally unaware of each other; they communicate with the base station/access point in a centralized manner, by using allocated frequency channels and time slots. In many cases, neighboring terminals present worst-case RF interferers to each other. Concept of collaboration encompasses a broad spectrum of ideas. Terminals aware of each other's proximity can use that information to minimize interference through cooperation; in an extreme case, collaborating terminals can expand the

system capacity by using packet-multihop or collaborative diversity.

IV. COGNITIVE RADIO TECHNOLOGY

Implementation of a cognitive radio with collaboration requires changes in all layers of wireless system, from physical layer up to the policy.

Spectrum sharing. One remarkable feature of the recent growth in wireless usage is that many of the new devices today are operating in the "unlicensed" parts of the spectrum that are explicitly meant to be shared for many uses. This openness to new users and uses spurred the deployment of new wireless systems. However, the amount of unlicensed spectrum currently used is limited and the way it is being shared it is far from perfect [4]. Co-existence of various systems that share the same band has not been cared of by their design, and has to be resolved in practice [5][6][7]. Because of legacy spectrum allocations there is little opportunity for opening new spectrum bands for licensed or unlicensed use. The most notable exception is 7GHz of bandwidth that has been opened for unlicensed use worldwide in the 60GHz band. However, propagation characteristics of the mm-wave frequencies favor indoor operation.

Judged by their recent moves and studies, the FCC appears to be receptive to secondary use of the spectrum; however, this use has been cautiously controlled. In a move to reclaim poorly utilized spectrum, the FCC has started allowing secondary use of frequency bands already allocated to primary users. UWB systems are allowed to operate in the 3-10GHz range given that their power spectral density is below the level of noise [8]. The FCC has also allowed for the secondary use of the unused channels in the UHF TV band, 400-800MHz [9], and a dual use of 700MHz band for commercial and public safety applications [10].

Radio architectures. The envisioned cognitive radio system necessitates the use of a wideband, frequency-agile wireless transceiver. Advances in the underlying communications and computing technology have evolved to enable us to devise dramatically different radio architectures from the one that has been in use for past 80 years.

In order to operate in a wider spectrum, a new, broadband radio architecture is needed. CMOS has been the technology of choice for commercial wireless systems for the past decade. Scaling of the CMOS technology increases its operating frequencies and reduces the device capacitances. This enables the design of radios that operate at higher frequencies and wider bandwidths, but with decreased linearity. Deeply-scaled CMOS, augmented by other technologies, such as MEMS can provide alternate means of filtering RF signals [15]. Such a wideband receiver is very sensitive to in-band interference, and active interference cancellation has to be embedded into the architecture [11][12].

Figure 2: Receiver architectures: a) super-heterodyne, b) direct conversion, c) software-defined, d) wideband.

The wideband radio architecture will evolve with technology: over time, it would be able to communicate over a broader band, and be more agile as technology advances.

In addition to the wideband and frequency-agile front-end, the wireless transceiver will need to have a dynamically configurable, wideband, power-efficient baseband processor.

Wireless receiver architectures have migrated from super-heterodyne with high IF frequency, Figure 2.a, to direct conversion with zero or low IF, Figure 2.b, to minimize the number of off-chip components in CMOS realization. Migration to wideband operation will require a further evolution of receiver architectures. Wideband operation is necessary in order for the radio to be able to scan over a wide spectrum and utilize unused spectrum in an opportunistic fashion. For instance, one can envision a transceiver operating in the 1-10 GHz band and continuously monitoring unlicensed WiFi, WiMax and UWB bands to maximize throughput and minimize power consumption. This requirement is difficult due to the widespread use of tuned elements (such as inductors) in the design of present day transceivers. On the other hand, a common vision of a software-defined radio [1], Figure 2.c presents a major challenge for the ADC design: Removal of the narrowband filtering before the ADC dramatically

increases the dynamic range of the signal, which, when coupled with the wide frequency band results in a very large power requirement. Technology scaling has been simultaneously improving the sampling frequency and power of ADCs; but the rate of progress removes this architecture from consideration in near future. Instead, a wideband architecture can be envisioned, where the tuned filters will be replaced with inductorless wideband filters, aided with active interference cancellation [13][14], to reduce the dynamic range requirements for the ADC, Figure 2.d.

Collaborative communication. Sixty years of information theory have led to understanding the capacity of individual point-to-point channels, its relationship to physical media, and methods to achieve channel capacity in practical systems. However, the idea of overall system capacity, a notion that is more relevant to shared media is largely undeveloped. By using cooperation between the devices it is possible to greatly increase system capacity.

Collaboration between wireless nodes can be used to reduce the probability of causing harmful interference in truly cognitive modes of operation. A single device has an unacceptably large chance of missing a primary user of the frequency band because of the finite chance that the received signal strength will be below the receiver's sensitivity, due to local fading. Multiple terminals, in collaboration with a communications broker have a better chance of detecting primary users.

Figure 3 describes how the aggregate capacity of large networks exploiting properties of wireless channels scales with the number of nodes n under various degrees of collaboration between terminals. When there is no cooperation and each terminal pair relies on long-range point-to-point communication, interference precludes simultaneous communication such that each pair only gets $1/n$ of the total bandwidth, and the total system capacity does not increase with n . Using packet multihop, communication can be confined to nearest neighbors, allowing more simultaneous transmission in the network, resulting in a total capacity scaling proportionally to $\sqrt{n}$ [16]. In contrast, by using more sophisticated cooperation techniques, it is possible to achieve a linear scaling of the network capacity [17] (and related [18][19][20][21]). The key theoretical idea is to have clusters of terminals form distributed antenna arrays to perform long range multiple-input-multiple-output (MIMO) transmission [22][23]. The cooperative MIMO transmission can mitigate interference, by joint processing of the received signals at each cluster, as well as perform beamforming for maximizing received power and range. These MIMO gains can be maximized by scaling the size of each cluster using hierarchical cooperation architecture to minimize overhead.

Figure 3: System capacity vs. node density as a function of degree of communication.

This theoretical result of linear system capacity increase with the number of users added presents a strong motivation for its implementation in a practical setting.

In order to operate in a cognitive mode, terminals have to be either allocated the open bands by the base station, or have to be able to sense the ‘white space.’ An individual terminal has limited ability of sensing a primary user operating in that area, as it always has a problem of being in a fade. Cooperation between a number of terminals can be used to greatly reduce the probabilities of misdetection and false alarms [24].

Wireless infrastructure. Technologies used for local communication, such as wireless LAN’s are being deployed over wide, metropolitan-size areas. One interesting possibility is to shift from having the wired infrastructure to be necessary for any operation, to viewing it as a performance-boosting accelerator for a system that could also operate purely wirelessly. Such a perspective leads naturally to systems that can bridge gaps that occur because of disabled base stations.

A system that is based on solely a wireless connectivity, where both the terminals and the connectivity points can interoperate between different systems, besides its ability to provide efficient commercial communications, provides a network that can operate even in major disasters.

V. CONCLUSION

Today’s wireless systems are limited by one hundred years of spectrum sharing, traditional narrowband radio architectures, limited cooperation within a system and between the system and the dependence on a wired infrastructure. Concept of cognitive and collaborative wireless communications, where vast amounts of spectrum are being used on a secondary basis through collaboration between the terminals, has a promise to dramatically expand the capacity of wireless systems.

ACKNOWLEDGMENT

Many of the ideas presented in this paper originated in discussions with author’s colleagues, professors and students at the Berkeley Wireless Research Center and the Wireless Foundations Center at UC Berkeley. In particular, the author thanks Robert Brodersen, Jan Rabaey, Ali Niknejad, Paul Gray, Anant Sahai, Adam Wolisz, David Tse, Kannan Ramchandran, Danijela Cabric, Ahmad Bahai, and Howard Shelanski for contributions to these ideas. The sponsors of the Berkeley Wireless Research Center are also acknowledged.

REFERENCES

- [1] J. Mitola III, “Cognitive Radio for Flexible Mobile Multimedia Communications,” *Mobile Networks and Applications*, Vol. 6, No. 5, Sept. 2001.
- [2] W.Krenik, A.Batra, “Cognitive radio techniques for wide area networks,” *Proc. 42nd Design Automation Conference*, 13-17 June 2005 pp.409 – 412.
- [3] D. Cabric, I. O’Donnell, M. S.-W. Chen, R.W. Brodersen, “Spectrum sharing radios,” *IEEE Circuits and Systems Magazine*, June 2006.
- [4] A. Akella, G. Judd, S. Seshan, and P. Steenkiste, “Self Management in Chaotic Wireless Deployments,” *MobiCom 05*, August 28-September 2, 2005, Cologne, Germany
- [5] N.Golmie, N. Chevrollier, O.Rebala “Bluetooth and WLAN coexistence: challenges and solutions” *IEEE Personal Communications*, Dec 2003
- [6] X. Jing and D. Raychaudhuri, “Spectrum co-existence of IEEE 802.11b and 802.16a networks using CSCI etiquette protocol,” *IEEE DySpan*, 2005.
- [7] S. Pollin, M. Ergen, M. Timmers, A. Dejonghe, L. Van der Perre, I.Moerman, F. Catthoor, and A. Bahai, “Distributed cognitive coexistence of 802.15.4 with 802.11,” *Crowncom*, 2006.
- [8] FCC, Revision of Part 15 of the Commission’s Rules Regarding Ultra-Wideband Transmission Systems, First Report and Order, February 14, 2002.
- [9] FCC, *Unlicensed Operation in the TV Broadcast Bands*, Notice of Proposed Rulemaking and Order, May 13, 2004.
- [10] FCC, *FCC Seeks Comment on Implementation of a Nationwide, Broadband, Interoperable Public Safety Network in the 700MHz Band*, Notice of Proposed Rulemaking and Order, December 20, 2006.
- [11] R. Gharipurey, S. Ayazian, “Feedforward Interference Cancellation in Narrow-Band Receivers,” *2006 IEEE Dallas/CAS Workshop on*

Design, Applications, Integration and Software, Oct. 2006 pp. 67 – 70.

- [12] H. Darabi, "A Blocker Filtering Technique for Wireless Receivers," *International Solid-State Circuits Conference, ISSCC'2007, Digest of Technical Papers*, San Francisco, CA, Feb. 2007.
- [13] F. Bruccoleri, E.A.M. Klumperink, B. Nauta, "Noise cancelling in wideband CMOS LNAs," *International Solid-State Circuits Conference, ISSCC'2002, Digest of Technical Papers*, pp. 406-407.
- [14] W.-H. Chen, G. Liu, Z. Boos, A. M. Niknejad, "A Highly Linear Broadband CMOS LNA Employing Noise and Distortion Cancellation," to appear at *IEEE RFIC* 2007.
- [15] J. R. Clark, W. Hsu, M. A. Abdelmoneum, C. Nguyen, "High-Q UHF micromechanical radial-contour mode disk resonators," *IEEE/ASME J. Microelectromechanical Systems*, vol. 14, no.6, 1298-1310, 2005.
- [16] P. Gupta and P.R. Kumar, "The Capacity of Wireless Networks", *IEEE Trans. on Information Theory*, vol. 42, no.2, 2000, 388-404.
- [17] A. Ozgur, O. Leveque and D. Tse, "Hierarchical Cooperation Achieves Optimal Capacity Scaling in Ad Hoc Networks", *IEEE Transactions on Information Theory*, vol 53, no. 10, pp. 3549 - 3572, October 2007.
- [18] S.Aeron, V. Saligrama, "Wireless Ad hoc Networks: Strategies and Scaling Laws for the Fixed SNR Regime", Preprint, 2006.
- [19] L.-L. Xie, P.R. Kumar, "A Network Information Theory for Wireless Communications: Scaling Laws and Optimal Operation", *IEEE Trans. on Information Theory*, vol. 50, no.5, pp. 748-767. 2004.
- [20] L.-L.Xie, P.R.Kumar, "On the Path-Loss Attenuation Regime for Positive Cost and Linear Scaling of Transport Capacity in Wireless Networks", Preprint, 2006.
- [21] A. Jovicic, S.R.Kulkarni and P.Viswanath, "Upper Bounds to Transport Capacity of Wireless Networks", *IEEE Trans. on Information Theory*, vol.50, no.11, pp.2555-2565. 2004.
- [22] G.J. Foschini, "Layered Space-Time Architecture For Wireless Communication in a Fading Environment when Using Multi-Element Antennas", *AT &T Bell Labs. Tech. J.*, vol.1 no.2, pp.41-59, 1996.
- [23] E. Telatar, "Capacity of Multi-Antenna Gaussian Channels" *European Trans. on Telecommunications, ETT*, vol.10, no.6, pp. 585-596, Nov. 1999.
- [24] S.M. Mishra, A. Sahai, and R. Brodersen, "Cooperative sensing among cognitive radios," *Proceedings of IEEE ICC*, Istanbul, Turkey, Jun 2006.