Connectivity Brokerage — Enabling Seamless Cooperation in Wireless Networks

A White Paper

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1. Executive Summary

The explosive growth in the density of wirelessly connected devices and their traffic load is raising the interference level and gradually leading to a **severe spectrum shortage**. Traditional approaches to address this challenge (such as spectrum regulation, improvements in spectral efficiency, and reducing cell sizes) are running out of steam or are facing operational roadblocks.

Fortunately, a number of approaches have been emerging from the research community that may help to address the looming spectrum crisis. These include dynamic spectrum allocation (known in its rudimentary form as cognitive radio), pro-active interference mitigation and cancellation, adaptive network re-structuring, etc. All of these approaches have a common set of properties: they require **coordination and cooperation between heterogeneous networking technologies**. This is not common practice in the wireless arena at present. Quite the contrary is true in fact: different wireless services actively compete for the same resources, and in the end adversely impact each other, leading to a major loss in capacity.

This can be addressed by the introduction of a general framework that enables diverse wireless technologies to **exchange information and to collaborate in a seamless fashion,** making a joint optimization of the scarce spectrum resources possible. To draw further on the Internet analogy, such a framework must be open, provide clear and robust abstractions, and be modular and scalable over a broad range of current and future technologies. In reference to the established practices in other fields where scarce resources are dynamically traded between competing interests (such as energy and commodities), we have coined our approach towards providing such a capability as **Connectivity Brokerage (CB).**

CB provides a universal architecture that enables diverse wireless networks competing for resources to actively exchange information and perform joint optimization in light of changing environmental and workload conditions, resulting in an improvement in the performance metrics of choice.

In this white paper, the basic concepts underlying the Connectivity Brokerage are described. To put the ideas in context, we first provide a bird's-eye view on the trends, opportunities and challenges in current and future wireless networking, as well as a discussion of the state-of-the-art in cooperative and collaborative wireless technologies. The potential of the Connectivity Brokerage is illustrated with a number of futuristic use cases. The paper is concluded with a "What's Next", elaborating on the future steps.

2. The Evolution of Wireless Networking – Observations, Opportunities, Challenges and Traps

To put the concepts and constructs introduced in this white paper into context, we first paint a general picture of the wireless-networking landscape of today, the potential of finding a long-lasting solution to the problems plaguing it, the challenges that may hinder the adoption of such a solution, and pitfalls to avoid. From this, the essential tenets of how that solution can be realized are deduced.

2.1 Observations

There is no doubt that wireless networking has made giant strides over the past two decades. Yet, the rapid adoption of wireless connectivity for a broad range of networking functions may cause it to be a victim of its own success, and could hamper its adoption for an even wider range of applications. To understand the potential roadblocks or showstoppers, it is worthwhile to enumerate a number of simple observations on the state of today's wireless networking.

Observation 1: Wireless traffic demand is growing rapidly.

With the deployment of 3G wide-area wireless data networks about a decade ago, the most excruciating question was whether demand would ever justify the atmospheric up-front capital investments cost – mostly associated with spectrum acquisition and infrastructure development. Barely a decade later, the answer is quite clear: the appetite for the wireless data networking is exceeding even the most optimistic projections. This broad statement is best illustrated with a number of charts. Figure 1 shows that, over a period of just 2 years, mobile data traffic has risen from a mere trickle to being au par with voice traffic in the European networks. Since then, the introduction of a number of popular smart phones has further accelerated the growth to the point of straining the existing infrastructure. In fact, wireless data overtook voice traffic for the first time in May of this year.

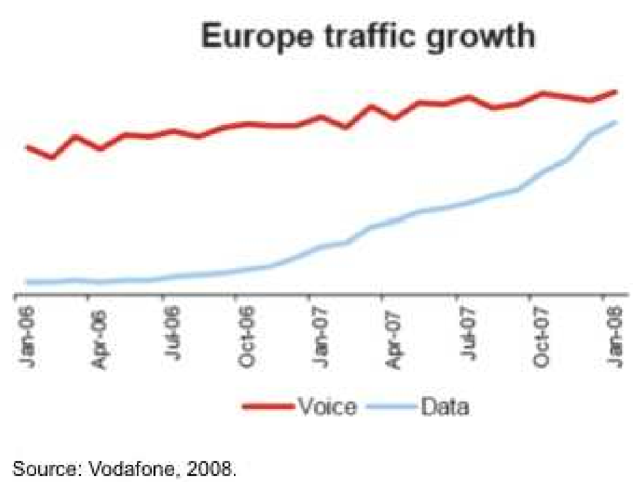


Figure 1: European wireless traffic growth over the period 2006-2008. (Source: Vodafone).

This trend is most likely to continue. Figure 2 shows a Cisco forecast of mobile data growth, predicting a 108% increase per year for the following 4 years (primarily driven by video). While such rates may hard to maintain over the long term, it shows that the demand for mobile data traffic is exploding.

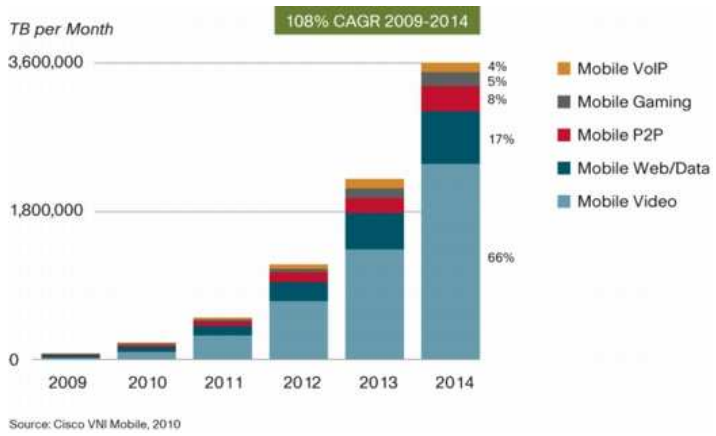


Figure 2. Cisco 2010 Forecast of Wireless Data Growth [CIS10].

Be aware that these numbers only include the Wide-Area networks. In parallel, local area wireless networks have seen an even faster rise, virtually eliminating wired networking for the last-hop connection to (mobile) compute platforms.

Example: The UK-based BT Openzone network, which runs 4,000 public Wi-Fi hotspots, has revealed that its data traffic doubled during 2009, and expects more of the same in 2010 [OPZ10]. The company claimed that the mass market adoption of Wi-Fi-enabled smartphones has significantly altered hotspot usage, with these devices accounting for the majority of access sessions in some locations.

Observation 2: The number of wireless terminals (and users) is growing even faster.

While the growth in traffic is stunning, the rapid adoption of wireless technology over the complete globe and the penetration through all layers of society is even more amazing. Over the span of 20 years, wireless subscription has risen to 40% of the world population, and is expected to grow to 70% by 2015! While one may assume that these numbers are bound to plateau sooner than later, this may not actually be true. Mobile terminals are getting more diverse, covering a wide range of shape factors and functionalities. Even fixed terminals are being equipped with wireless interfaces (think, for instance, about entertainment systems, game machines and appliances). However, the fastest growth will in most likelihood occur in the “sensory swarm” [RAB08]. It is being projected [UUS07] that by the beginning of the next decade there may be trillions of wireless sensors deployed worldwide, fulfilling diverse functions such as environmental and infrastructural monitoring, energy management, advance healthcare, etc. The idea that there may be more than 1000 radios deployed per person on earth in the foreseeable future is truly mind-boggling.

Example 1: Global shipments of short-range wireless ICs (Bluetooth, NFC, ultra wideband or UWB, 802.15.4, Wi-Fi) are expected to surpass two billion units in 2010, increasing approximately 20 percent compared to 2009. Shipments are forecast to total five billion in 2014, according to new market data from ABI Research [EET10]. Bluetooth ICs makeup a significant part of the total short-range wireless ICs shipments, says industry analyst Celia Bo. Bluetooth takes more than 55 percent, followed by Wi-Fi at around 35 percent; the rest of the shipments are made up of NFC, UWB and 802.15.4 ICs.

Example 2: "… We believe that these trends will drive the Wi-Fi attach rate to 40% of all handsets in 2014. This attach rate translates to mobile Wi-Fi chip shipments (including combos) of 750 million units in that year, a 28% annual growth rate from 2009." [LIN10].

Observation 3: Wireless traffic is getting more diversified.

Another trend is that the "nature" of the bits that are being transmitted over the wireless medium is rapidly becoming more diversified, posing a broad range of demands on the network. With voice transmission being the first large-scale application of wireless networking, emphasis was on providing coverage and guaranteeing sufficient bandwidth to carry voice streams, while ensuring that latency constraints were met. Wireless Internet access, the first outcome of the broad adoption of Wi-Fi and 3G data networks, initially was purely throughput-oriented. The increasing popularity of multimedia streaming over the Internet has introduced a number of additional requirements such as average data-rate guarantees. Interactive applications such as Voice-over-IP (VOIP), videoconferencing, gaming and virtual reality added extra constraints in terms of latency (See: Figure 2, Table 1). A totally different set of expectations is set for the emerging wireless sensor network applications, in which the aggregate data traffic tends to be bursty, may or may not be periodic, and is most often subject to very stringent reliability requirements. Finally, security, privacy and safety considerations vary widely over different application domains. All these considerations seem to indicate that a vision of a single networking solution that encompasses all applications is most probably utopian.

Application	Reliability	Delay	Jitter	Bandwidth
E-mail	High	Low	Low	Low
File transfer	High	Low	Low	Medium
Web access	High	Medium	Low	Medium
Remote login	High	Medium	Medium	Low
Audio on demand	Low	Low	High	Medium
Video on demand	Low	Low	High	High
Telephony	Low	High	High	Low
Videoconferencing	Low	High	High	High

Table 1. Requirement variations over Internet applications.

Observation 4. Heterogeneity (in wireless technologies) is here to stay.

In an ideal world, one may envision a single technology that addresses all the wireless needs. Indeed, a uniform approach may seem to make it a lot easier to improve spectral efficiency. In reality, this is very unlikely to happen – and may even be undesirable. The wired networking world can serve as an example of why heterogeneous networking solutions actually may be the better option. Differences in communication distance (long- versus short haul) and types of data traffic (voice, video, data) have led to different solutions, such as Firewire and USB, Ethernet, ATM and optical WDM. The same is definitely true in the wireless world, where the diversity may be even larger. Differences in traffic properties, coverage, spectrum band, terminal and infrastructure cost, and energy efficiency have led to the adoption of a broad range of solutions, ranging from narrow-band to ultra wideband, from managed to ad-hoc or peer-to-peer, and from licensed to unlicensed. The truth of the matter is that heterogeneity is here to stay.

Observation 5: Interference is increasing.

With the rapid growth of wireless data traffic, the increasing number of terminals, and the diversity of non-coordinated technologies being deployed, it should come as no surprise that interference is on the rise. The most essential property of wireless networking is that it is a broadcast technology; that is, all links or networks in essence interfere with each other. The traditional approach is to separate competing technologies through spectrum regulation. Unfortunately, that strategy has led to a fracturing of the electromagnetic spectrum (ranging from a few Hz to 100 GHz), which is already apparent from a first glance at the FCC frequency allocation chart. Many bands are assigned to dedicated functions, and, hence, often suffer from low utilization. The amount of spectrum available to general public usage (where a lot of the recent growth has happened) has grown only piecemeal over the past decade, and there are no indications that this may drastically change over the coming years.

Example: The best illustration of the rapid growth in interference is offered in the 2.4 GHz ISM band, where technologies such as Wi-Fi, Bluetooth (BT), Zigbee, DECT and NFC compete. A recent measurement at the Berkeley Wireless Research Center (BWRC), located in the center of Berkeley, revealed that across the area of 12,000 sq feet 63 Wi-Fi access points (AP) could be identified! While the observed signal power from these APs varied substantially and not all were true interferers, the message is quite clear. A number of studies have confirmed this crowding of the ISM band in metropolitan centers (e.g. [DOJ04] and Figure 3). The introduction of higher data rate networks (e.g. 802.11(n,ab,ac)) only increases the interference.

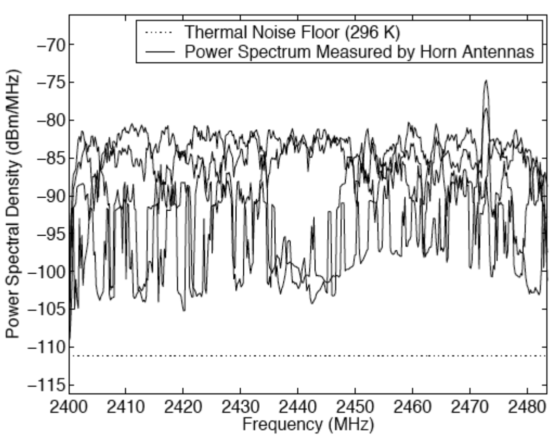


Figure 3: Spectral crowding of the ISM band in urban sites – the San Francisco Bay Area in this case (from [DOJ04]).

The resulting interference directly impacts the quality of the delivered service. With more applications relying on strict quality-of-service guarantees, further deployment and adoption may be jeopardized if interference levels are allowed to further increase. More likely, a reduction is needed.

Observation 6: Traditional capacity improvements are running out of steam.

The response of the wireless research community and industry to the increase of traffic has been to increase the capacity, through a variety of regulatory and technological improvements. And indeed, they have been very successful at it, as captured by "Cooper's Law" [ARR10] which states that wireless capacity has doubled every 30 months over the last 104 years (Figure 4). This translates into an approximately million-fold capacity increase since 1957. In the paper, these gains are broken down as follows: a 25x improvement from wider spectrum, a 5x improvement by dividing the spectrum into smaller slices, a 5x improvement by designing better modulation schemes, and a whopping 1600x gain through reduced cell sizes and transmit distance.

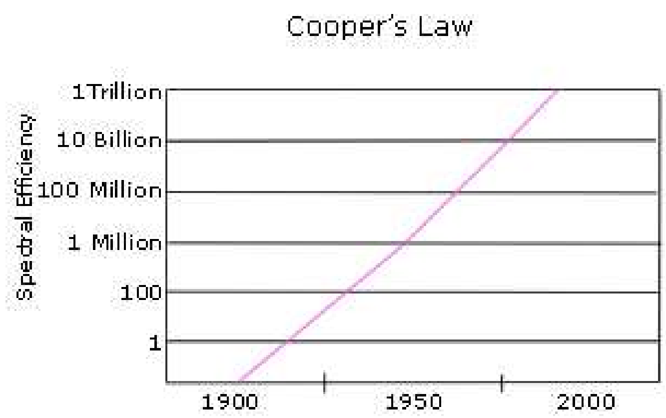


Figure 4. Cooper's Law, documenting the growth in wireless capacity over the past 100 years [ARR10].

Maintaining Cooper's Law in the coming decades may not be trivial. Opening up more spectrum for general usage through re-assignment or through dynamic assignment obviously would be a major help.

The broadband plan for America [BBP10] recommends that the FCC make 500 MHz newly available for broadband use within the next 10 years to sustain the growth in demand; 300 MHz between 225 MHz and 3.7 GHz should be made newly available for mobile use within five years. It also recommends that the FCC expand the opportunities for innovative spectrum access models.

Advanced modulation and coding schemes, interference cancellation and novel media-access mechanisms have reached a level of sophistication that make further progress at the physical or link level extremely hard. This is illustrated in Figure 5, which plots the spectral efficiency improvement over the various mobile WAN services. Many wireless systems now operate close to the Shannon limit. Progress is still being made through the usage of spatial diversity, with techniques such as MIMO. However, even this strategy will be exhausted soon. To quote Roberto Padovani, CTO of Qualcomm, "With wireless networks now operating close to the Shannon limit, improvements at the physical link layer will be very hard to come by in the coming years.

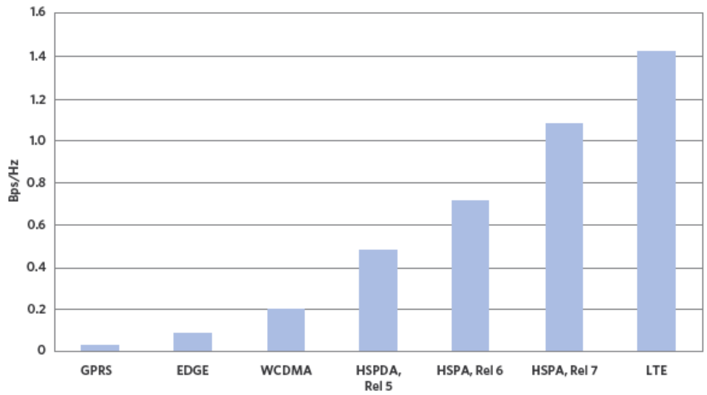


Figure 5. Evolution in Spectrum Efficiency [BBP10]

Cell size reduction is still an attractive option. An example of such is the Femtocell model that is promoted by many WAN providers these days. True realization requires however a change in business models, and the overcoming of some socio-economic hurdles.

It thus seems that the prospects for further capacity improvements are dire. Fortunately, in recent years a number of innovative ideas have emerged to broadly increase the available wireless spectrum, or, more precisely, mitigate the limiting effects of interference. The adoption of these techniques can give a boost to the further growth of wireless networking of all types.

2.2 Opportunities

In light of the observations above, the opportunity lies in the enabling of heterogeneous technologies and applications to co-exist in a manner that maximizes the spectrum utilization and minimizes the mutual interference, while exploiting the opportunities offered by flexible spectrum allocation. This requires a strategy to **keep interference at bay through coordinated interference mitigation schemes at all levels of the system hierarchy**.

Research in information theory and communications and networking systems over the past decades has led to a number of opportunities that can be categorized under the following headings:

Opportunity 1: Cooperation

This is the most generic approach. Even a minimal cooperation between various heterogeneous technologies can lead to better spectrum utilization or reduced interference. To understand what this means, it is worth examining the exact semantics of "cooperation". The Wikipedia definition is actually quite revealing:

> *"**Cooperation** is the process of working or acting together, which can be accomplished by both intentional and non-intentional agents. In its simplest form it involves things working in harmony, side by side, while in its more complicated forms, it can involve something as complex*

as the inner workings of a human being or even the social patterns of a nation. It is the alternative to working separately in competition …"

Cooperation can be as simple as having various wireless networks, sharing the same frequency bands, observe the impact on their performance and act accordingly to mitigate the impact. This approach falls under the "non-intentional" cooperation model. A more pro-active approach is to have interfering networks exchange information regarding observations and intent – avoiding second-guessing. It is no surprise that this uniformly leads to better results. Even better, those networks could actually choose to actively work together and negotiate how the best is obtained for all. The latter is more demanding, and falls under the "collaboration" category, described next.

Cooperation Examples:

- Some of the more advanced Wi-Fi protocols fall into the "non-intentional" cooperation category. The IEEE 802.11k standard has been developed to support seamless terminal transitions in WLAN networks, by *providing information to terminals* to select the best available access point [11K08].
- The cognitive radio approach [MIT99] can be classified as "intentional" cooperation, as the whole concept is centered on the idea of observation and avoidance of interference to "primary owners".
- Overall, active cooperation with sharing of information between multiple heterogeneous networks is still a novel concept in the wireless world. To our knowledge, no such system is in operation today.

Opportunity 2: Collaboration

Even more effective is to have terminals or networks competing for the same resource (that is, spectrum) to actively collaborate and strive for a solution that accomplishes the best for all. Again, the Wikipedia definition of collaboration provides a wealth of useful insights.

Collaboration is a recursive process where two or more people or organizations work together in an intersection of common goals by sharing knowledge, learning and building consensus. Most collaboration requires leadership, although the form of leadership can be social within a decentralized and egalitarian group. In particular, teams that work collaboratively can obtain greater resources, recognition and reward when facing competition for finite resources.

Over and beyond cooperation, collaboration requires building consensus. In general, this means some form of optimization to balance the often-conflicting requirements between needs and resources. A number of groundbreaking insights over the past decade have unequivocally established that collaboration can lead to capacity improvements over and beyond what could be accomplished by pure physical layer advancements (curtailed by the Shannon limit).

Collaboration Example 1: Mesh Networking – In a landmark paper in 2000 [GUP00], Gupta and Kumar established that the concept of mesh networking (in which users connect to each other and to the infrastructure in an ad-hoc multi-hop mode) actually increases the wireless capacity of a network by a factor of $\sqrt{N}$ (with N the number of users/terminals). While this still means that the capacity per user is reduced by a factor of $1/\sqrt{N}$, this is substantially better than what can be accomplished in a cellular structure, where the capacity/user scales as 1/N (Fig. 6 - a,b). Mesh networking is a pure example of collaborative networking, as it requires a user to forward packets generated by others, depleting some of his own resources. This is more than offset by the win at the global system level. For example, the IEEE 802.11s and 802.15.5 standards are now trying to provide a set of guidelines for the deployment of mesh networks.

Collaboration Example 2: Collaborative MIMO – Even larger capacity gains can be obtained by going one step further. The collaborative MIMO concept [OZG07] creates the perception of a large distributed antenna by transmitting a single packet simultaneously through multiple terminals. In its ideal form, this has the potential of increasing the network capacity by a factor N (the number of terminals), hence keeping the capacity/user constant independent of the number of users (Fig. 6c).

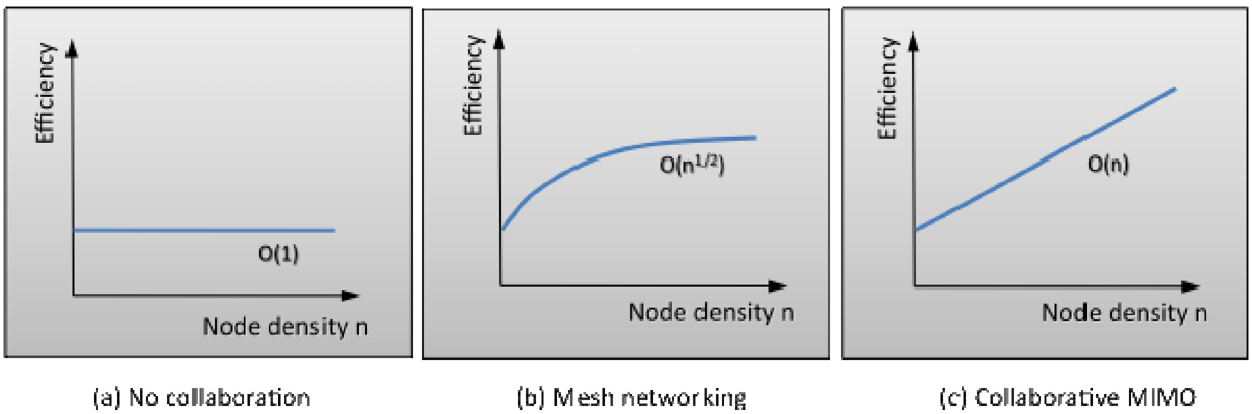


Fig. 6. Impact of node density on cell capacity for various collaboration schemes.

Opportunity 3: Adaptation

It is universally true that networks experience large variations in terms of demand and workload volume and characteristics. Wireless networks have the additional property that the propagation medium can undergo large temporal variations over a broad range of time constants caused by effects such as fading, shadowing, mobility, and interference. Instead of trying to address the variability only at the design time of the network, substantial improvements in efficiency and reliability can be obtained by adopting a system approach that adapts dynamically to changes. The Wikipedia definition of adaption once again sheds light on what this entails:

> *Adaptation is the evolutionary process whereby a population becomes better suited to its habitat.*

The concept inherently assumes an underlying control system: elements of the population observe changes in the environment, and decide individually or jointly to adjust their behavior so as to maximize the individual and global good under the revised environmental conditions. Adaptation is a commonly used strategy in modern wireless technologies. An example is power control, in which the power level of individual transmitters is dynamically adjusted to minimize energy dissipation of the individual terminals while minimizing the overall interference under dynamically varying conditions (of channel quality and position of the terminals). Yet, adaptation at a grander scale (intra- and inter-network) is still rarely used. It requires a distributed control strategy that combines sensing, optimization and actuation over network boundaries.

Example 1: Today's 802.11 systems adapt the choice of modulation scheme used (and consequently the data rate) to the observed quality of link.

Example 2: Cognitive Radio [MIT99] is a more advanced example of a wireless adaptive technology. Based on sensing of the environment and the detection of the presence of the "primary users", a secondary user must make a decision on where to move next. Clearly, this approach in its purest form translates into adaptive and dynamic spectrum allocation. With some imagination and creativity, it is possible to derive a broad range of operational and business models that result both in better spectrum utilization and better revenue/Hz than the static model of today.

2.3 Challenges and Traps

Cooperation, collaboration and adaptation are powerful mechanisms that may offer the best possible answer to the growing demand for wireless connectivity in a spectrum-starved world. Yet, true and effective deployment requires that a number of formidable challenges be overcome:

Challenge 1: Complexity and Dynamism

As mentioned earlier, effective interference mitigation requires nothing less than a distributed control system, including sensing, optimization and actuation. In fact, the proposed systems display all features that are the hallmark of complexity: large number of interconnected heterogeneous components, non-determinism and non-linearity. In addition, the very nature of wireless connectivity featuring dynamic components with widely varying time constants considerably adds to the challenge.

The design, verification, deployment, test and management of such a complex distributed system are notoriously hard, unless addressed using a structured and formalized approach. Failing to do so most probably will lead to unreliable and unmanageable networks. The history of complex system design has shown that the only workable approach is to establish a framework based on well-defined abstractions with clean hierarchies and interfaces, enabling modular design and simple composition. This is exactly the approach advocated in this white paper.

Challenge 2: Socio-Economic and Cultural Barriers

These may present an even more formidable challenge. In the wired network arena, concepts such as the Internet enabled the federation of vastly different networks, in which a single packet can traverse a number of diverse networks, operated by different entities. As stated, this approach does not suffice in the wireless arena, where better utilization of the shared spectrum resource requires cooperation and collaboration. The wireless culture of today certainly does not support these concepts, and suffers from technology diversity, diversity of ownership models, and conflicting operational models in terms of spectrum ownership (licensed versus unlicensed), execution strategies (centralized versus distributed), and monetization approaches (free versus pay-per-use or subscription based). Any framework that intends to enable cooperation and collaboration must present means to address these hurdles in a flexible and agile fashion, making it possible for various models to seamlessly coexist. An additional issue is that the pure concept of collaboration may run into sociological or cultural roadblocks that can only be resolved by proper incentives.

Example: Mesh Networks. Consider again the case for mesh networks. It is clear from a system perspective that a multi-hop approach leads to better capacity, better overall energy efficiency (because of the smaller cell size), and potentially higher reliability due to the inherent redundancy. Yet, from an individual user perspective, these gains may not be that obvious. Your first reaction may be that routing someone else's packets takes away personal energy resources — forgetting that the energy cost of your own packets becomes cheaper as well. In addition, the forwarding approach comes with increased vulnerability to malicious interventions. Only security guarantees and financial incentives can help to allay the "trespassing of private property" concerns.

Before embarking on a description of the proposed framework, it is worth outlining some common traps that must be avoided.

Trap 1: Business as Usual

This is unfortunately the prevalent attitude. Many players in the wireless arena believe that their model is the answer to all, and use all their muscle to make it prevail. This has landed us into the situation we are in today with vast underutilization of spectrum.

Trap 2: Dedicated Solution

Another scenario is one in which parties with interfering technologies sit around the table, and figure out how to mitigate the impact of that interference – often through the introduction of the novel operational procedures or modifications to the standards. While this is a step in the right direction, this bi-lateral approach often leads to ad-hoc non-scalable solutions, and only unlocks a small fraction of the potential benefits of cooperation. It for sure does little to address the fragmentation of the wireless networking world.

Example: The 802.11k standard [11K08] is a first step in the direction of information sharing between Wi-Fi access points and their terminals. Similarly, standardization bodies have been trying to come up with solutions to address the coexistence problems between Wi-Fi and Bluetooth in the 2.4 GHz band (e.g. IEEE 802.15.2 and IEEE 802.19). All these approaches tend to be ad hoc, and are totally reactive. Any new technology emerging in overlapping bands will cause exactly the same problems to occur again.

Trap 3: Universal Solution

Another trap is the belief among some that a single “unified” wireless technology may emerge that addresses all the wireless needs and demands over all spectrum bands. For example, some state the LTE-Advanced may be just such a solution. This is most probably just utopia; as stated in our “Observations”, the needs of the various wireless services are too diverse to be accommodated by a single solution. Heterogeneity is here to stay.

Trap 4: Over-specification

A final trap to be avoided is attempting to construct a framework that is overloaded and overspecified. The most effective frameworks are those that are light and concentrate on the essential abstractions and definitions. This enables the broadest possible adoption, avoids the incorporation of elements that are relevant only for a given technology or application, and leaves the door wide open for innovation.

Example: A beautiful example is the Internet Suite Protocol (TCP/IP), which was intentionally left very light and purely functional. This is why the protocol still survives today almost 40 years after its introduction. An opposite example is the overly specified and complicated Asynchronous Transfer Mode (ATM) protocol.

2.4 Solution Outline

The preceding discussions help to outline the necessary characteristics of a universal framework that would enable the seamless cooperation and collaboration between interfering heterogeneous wireless networks.

To be truly general, it must possess the following general properties:

- **Open.** It has been demonstrated over and over again than only open frameworks can attract the necessary following and critical mass. While it is true that innovation occasionally emerges from closed environments, the introduction of concepts that have a broad impact on the community in general requires a broad participation, and openness is an essential ingredient for that.
- **Easily Extensible and Scalable.** This goes without saying. As we don’t know what the future holds, any successful framework should leave room for innovation. Scalability is essential to ensure that the growth in demand for wireless traffic can be accommodated.
- **Adaptive.** Dynamism is one of the most essential features of wireless communications, and addressing it appropriately can make a major dent in the spectrum shortage and improve reliability of wireless networks.
- **Resilient.** Single points of failure are not acceptable. If executed well using a distributed and dynamic architecture, the framework could help to ensure availability even under the most extreme conditions (such as natural or environmental disasters).
- **Technology-agnostic.** Including any element that is specific to a single technology should be avoided, as these components typically do not age well and tend to cause unnecessary restrictions.

Similar considerations makes us conclude that the framework should be agnostic of the OSI layering structure as well, and be capable of equally supporting opportunities at any layer.

- **Friendly to legacy systems.** Again, this goes without saying. Given the enormous amount of legacy systems out there, an effective way to grandfather or incorporate them into the framework is absolutely essential. Depending upon the approach, integration can range from non-intentional cooperation to active collaboration.

In addition, lessons of the past have helped to formulate a number of overlaying guidelines:

- **Specify no more and no less than is needed.** Avoid over-specification and make the basic framework constructs as simple as possible.
- **Identify the right abstractions.** This is the true essence. Complexity, universality and scalability all are intimately coupled with the right choice of the abstractions.
- **Translate them into simple well-defined interfaces -** the practical tools of the system developer.

The Connectivity Brokerage (CB) framework for seamless cooperation between wireless networks has been developed with the above considerations and observations in mind. Its overall concepts are defined in Section 4. To put this in context, it is worth preceding it with a short survey of the state of the art in cooperation and collaboration in wireless networks.

3. Cooperation and Collaboration in Wireless Networks – A Birdseye View on the State-of-The Art

3.1. Overview of Cooperation and Collaboration Techniques

The concept of cooperation in wireless networks is not new. It has been used in the past to address some of the fundamental challenges of wireless communications: the limitations in coverage/quality of delivery due to channel variability, as well as the impact of interference. While some of the approaches may (at least partially) address both, most of them primarily deal with only one. Therefore we have split the overview along these lines.

A. Cooperation for Quality improvement / Range Extension

A broad range of techniques has been proposed to ensure reliable quality in light of varying environmental conditions. We have roughly classified these ideas along the lines of the level of the network stack they are operating at.

Link Adaptation

The most basic approach to keeping the bit/packet error constant in spite of changing channel conditions is to **adjust the transmission rate and/or power**. To enable this, at least a minimal form of cooperation with the communication partner is necessary. Some systems use very rudimentary feedback –e.g. the Immediate ACK per packet in WLANs–, but proper rate adaptation under these conditions poses a real challenge [PRO07]. It should be no surprise that better knowledge of the channel quality leads to more efficient adaptation [WON06]. In many of the approaches discussed below, we will implicitly assume that some feedback on the channel quality, provided at a pace comparable to the channel changes, is available.

Exploiting Spatial Diversity

A very attractive approach to optimize throughput or quality of a wireless connection is to exploit spatial diversity. This is apparent from the huge interest in multi-antenna systems today. However, spatial diversity can also be effectively utilized in cooperative systems comprised of terminals with single antennas. If a group of terminals has good connectivity to each other (for instance, because of their close proximity), they may cooperatively create a long-haul link to a receiver or a cluster of receivers not belonging to the group [ASA09]. This can be visualized as the group of terminals jointly forming a large distributed antenna array. This concept is naturally extendable to multiple receivers, creating a **collaborative MIMO** structure.

An alternative approach to the creation of spatial diversity is the use of **relaying** [See DAV09]. Rather than transmitting a packet directly from A to B, an intermediate hop over C is introduced. This pays off only if the connectivity on each of the two hops is significantly better than the direct route. Most relay approaches are confined to the physical layer using either an analog "record and forward" or a digital "decode and forward" (with proper use of coding) method. Mesh networking, highlighted earlier, raises the bar to another level. As noted, having nodes collaboratively work together to support each other's communications results in a net increase in capacity.

For all these schemes to become useful in reality, a lot of cooperation is needed at the higher levels, some of which may require quite complex protocols. Just to name a few: candidates for collaborative MIMO and relaying have to be elected based on potential gains; the proper parameters and settings have to conveyed; and incentives for sharing have to be created and security concerns overcome.

Coordinated Network Selection

Frequently, a terminal has the option to connect to the wired infrastructure via one of several available networks. The selection of the best-suited one is mostly the result of operational decisions. Historically, the terminal makes this decision by itself based on some observable parameters such as the measured strength of signals received from the "candidate" access point [ARB03]. A more informed decision could be made if additional information – like the cumulative load of individual base stations or the capacity of their wired backbone – is taken into consideration (see [ABU06], for instance). This requires cooperation with the base stations (BS) / access points (AP) that goes beyond what is available today. Further improvement can arguably be accomplished by holistically considering a broad population of terminals, taking into account their traffic demands and mobility patterns. This assumes gradually increasing levels of cooperation in information exchange, decision making and decision distribution/implementation among both terminals and BS/APs. The problem of BS/AP selection has been intensely studied for homogeneous technologies – in fact, widely deployed solutions exist for cellular systems and WLANs. In both cases, the amount of flexibility is a strong function of the operational business model(s); that is, the ownership of the BS/APs by one or more operators, and the existence of mutual agreements.

The increasing availability of multi-standard terminals opens the door for an even broader question: how to dynamically select between different networking technologies (e.g. WLAN versus cellular 3G femtocells, or Bluetooth versus Wi-Fi). These so called **heterogeneous handover strategies** have recently been promoted as an attractive way to improve performance (see e.g. [KAS08]). While having the individual terminals make this decision is indeed possible (based on the perceived cost of connectivity or the expected QoS), better overall results in terms of network capacity can naturally be obtained if the global cost (in terms of resources) is considered. A simple example can help to ground this statement: a terminal further away from a BS/AP uses more resources, hence moving it to another network leads to a net overall win.

Network Coding

Additional opportunities for quality improvement arise when considering wireless traffic at the network level. For instance, coding has been a very effective tool in providing better performance at the link level. Yet, further gains in overall throughput of a wireless network can be obtained by using an approach called network coding. While trying to explain the concept in depth is out of the scope of this paper (for a more in-depth look, please refer to [FRA06,FRA07]), a simple example can help to convey the basic idea: Assume a broadcast system with a Base Station (BS) and two terminals that can only communicate via that base station. It is sufficient for the BS to retransmit a message coming from Transmitter A bitwise XOR-ed with a message from Transmitter B, rather than retransmit each of these messages separately, leading potentially to a throughput increase. This scheme is only effective if traffic to both A and B is available – hence, coordination in the scheduling of data traffic is necessary.

B. Cooperation for Interference Mitigation

As wireless communication relies on broadcasting over a shared medium (spectrum), it inherently carries the risk of conflicts that may temporarily inhibit functionality to some of the players. Within the confines of a single system, the negative effects of this can be contained by adopting some unified rules of operation assuring medium-access in an efficient and fair way to the multiple parties involved. This usually is done through some form of Multiple Access Control (MAC) mechanism where the aim is division of the available capacity with minimal loss.

In contrast to this coordinated medium sharing, this section addresses “real” interference, which is the adverse influence that two or more independent groups of terminals have on each other when attempting to share the same medium. This adversity translates de-facto into a loss of capacity. In general, it has been observed that deployment of differently organized systems in a non-orthogonal space of radio resources has a high potential of adverse interference, as has been documented extensively for the ISM band. The goal of **interference mitigation** is to minimize that loss. Two fundamentally different approaches can be identified: (1) avoid or limit the amount of interference (typically measured in terms of interference power); (2) improve the robustness of a link against a given level of interference.

The most classical approach to **interference avoidance** is traditional (static) frequency partitioning/spatial frequency re-use, in which a given frequency band can only be used if the spatial distance between competing services is large enough to ensure that the interference level falls below a given threshold. Another standard approach to control interference and coverage is to apply power control to base stations and access points [QIA07]. The concept of “spectrum reuse” opens the door for a more dynamic approach, in which third parties are allowed to temporally exploit spectrum under the condition that its owners (“primary users”) are not using it. A number of mechanisms have been proposed, included usage databases and owner-supported reuse. In virtually all cases, it requires sensing the activity of the primary user (performed either by individual terminals or through collective sensing) [MIS06b].

The **interference robustness** of a link can be improved by the proper choice of modulation and coding schemes. An interesting combination of both schemes can be found in the “partially-overlapping channels” approach, where the tolerable threshold for interference to neighboring cells is not defined as an absolute value, but is set based on the individual robustness of those cells [e.g. VIS09 for WLAN cells].

Interference cancellation goes one step further, and allows for signals to be successfully received in spite of the presence of an interferer with significantly higher power. In a nutshell, cancellation proceeds in two phases: (1) the interferer’s signal is decoded out of the received signal mix, and (2) the coded/modulated version of the interference signal is subtracted from the mix using signal processing techniques.

To be truly effective, most of the above schemes require varying degrees of cooperation. This is especially the case for some of the most advanced schemes, in which explicit harmonization of parameters and scheduling in competing technologies is used to mitigate interference [GUM09].

3.2 How to Enable Cooperation and Collaboration?

In the preceding paragraphs, we have presented a bird’s eye view of the different cooperative approaches that have been proposed to improve the quality of wireless networks. All attempt to ensure better utilization of the available resources by providing some form of orthogonalization between competing services over one or more of the following dimensions: frequency, time, space, or representation (code). When this is performed in a static way it can lead to huge waste, as resources are set aside needlessly. But when performed dynamically it can lead to major improvements. The execution of these dynamic scenarios requires two components: (1) dynamic optimization and decision making, and (2) communication of observed system and environmental state.

Optimization and Decision Making

Most strategies in vogue today fall in one of the following two opposing classes:

- **Localized, distributed decision making**, in which each participant follows some local strategy. Obviously, to arrive at some globally acceptable result, the individual policies should be harmonized to some degree. Frequently, the recommendation is to follow one single specific local policy. Examples of such are the selection of access point or the choice of the power settings in wireless LANs.
- **Centralized decision making**. This requires that the entity making the decision be provided with the necessary data. Protocols to support such information gathering have recently started to emerge, but are usually restricted to a single technology. An example of such is 802.11 k [11K08].

Information Exchange

Any attempt to effectively cooperate includes the necessity to exchange data. In wireless systems working on different channels (and possibly changing the channels frequently, or being active for only short fractions of any given time period), assuring the exchange of signaling data is by far from trivial. Several approaches have been proposed:

- Use of locally reserved dedicated channels, assumed to be well known. For example, the establishment of a local Cognitive Pilot Channel has been proposed in Europe [PER07].
- Use of one of the local free channels. For this to work, interested parties must first come to an agreement, e.g. though a rendezvous protocol [Lin04].
- Use of overlay channels, for instance based on UWB signaling [BRO04].

While cooperation seems to be pretty natural within a single network belonging to a given administrative management domain, harmonized operation of separately managed networks is neither easy nor natural. The Ambient Networks Project [See e.g. KAP05] has proposed a Network Composition approach to support different forms of harmonized joint service.

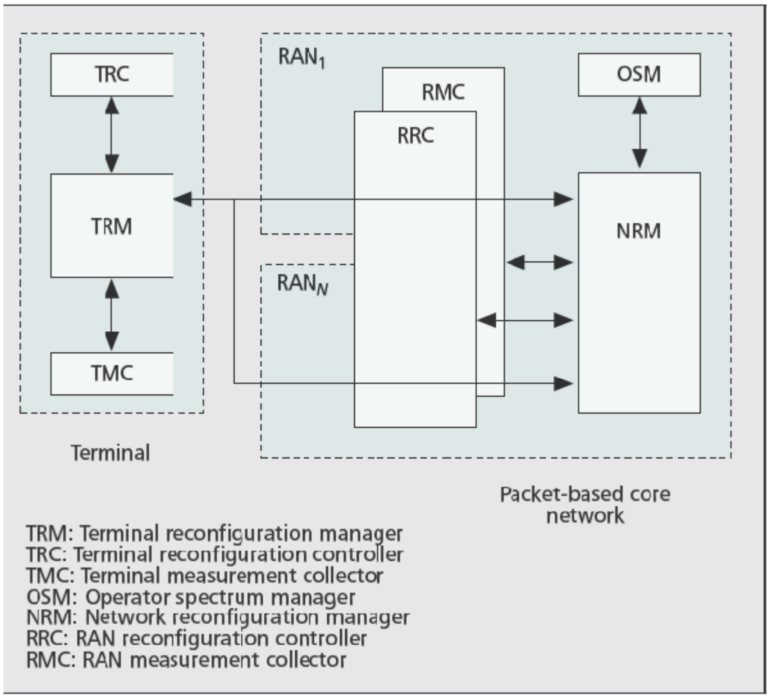
Even assuming that there are means to exchange information among several networks, and that decisions can be made about parameter settings to be imposed on components of these networks, assuring that all components involved will execute the desired decisions “synchronously” is not simple. In fact, in the most general case this implies a distributed consensus, which is known to be difficult. Some ways to handle this have been discussed in [AYA04, WHU07].

Combining the Two

A truly general framework for cooperation and collaboration has to be capable of information exchange between all networks and technologies involved, and must support any form of decision-making, while also taking care of all other aspects of collaboration such as establishment of rules and policies.

A number of efforts have been recently reported that address exactly these issues. Examples of such are the ETSI RRS effort [RRS10] and the IEEE 1900.4 standard [1900.4].

The IEEE 1900.4 standard, released in the spring of 2010 [1900.4, FIL08], comes close to meeting the stated requirements. It proposes a general architecture for radio resource management with the stated purpose “to improve the overall composite capacity and quality of service of wireless systems in a environment with multiple radio-access technologies by defining an appropriate system architecture and protocols which will facilitate the optimization of radio resource usage, in particular, by exploiting information exchanged between network and mobile terminals, whether or not they support multiple simultaneous links and dynamic spectrum access." This effort confirms the importance of cooperation, and presents an important step forward towards an approach that goes beyond a single technology.



An overview of the IEEE 1900.4 architecture is shown in Figure 7. It presents a number of architectural building blocks comprising (i) network resource managers, (ii) device resource managers, and (iii) the information to be exchanged between the building blocks. The building blocks are assumed to be capable of communication with each other, although the standard does not define how.

Fig. 7: The P1900.4 Architecture. A RAN is a "radio access network" [1900.4, FIL08].

While definitely offering a number of major steps forward, the IEEE 1900.4 standard has some important shortcomings in light of the recommendations of the previous section. Most importantly, the architecture seems to be primarily inspired by a wide-area cellular perspective. This has impacted the partitioning of the functions over the different managers (such as the NRM, RRC and RMC), leading to a rather complicated definition of the interfaces and interplay between the different managers. Ultimately this impacts the universality and scalability of the approach (for instance, extending this approach to local-area and ad-hoc networks is non-trivial). As pointed out, this concern can be addressed by the introduction of clear and universal abstractions (and associated interfaces). In addition, IEEE 1900.4 focuses on slowly varying situations with no means of assessing time synchronization aspects, implicitly excluding cooperation at the PHY and MAC layers. This leaves a large range of opportunities for spectrum optimization off the table (as was established in the previous sections). The good news is that the 1900.4 standard is in many ways compatible with the Connectivity Brokerage ideas promoted in this paper, making it relatively easy to develop interfaces and encapsulations between the two.

4. Connectivity Brokerage – The Concepts

The true potential of collaborative approaches is achieved only by a **generic solution** that enables information exchange and network optimization over a broad range of current or future wireless technologies in a modular and scalable fashion. In reference to the established practices in other fields where scarce resources are dynamically traded between competing interests (such as energy and commodities), we termed our approach Connectivity Brokerage (CB).

To restate our definition from section 1, *CB provides a universal architecture that enables diverse wireless networks competing for resources to actively exchange information and perform joint optimization in light of changing environmental and workload conditions, resulting in an improvement in the performance metrics of choice.*

Note that the CB exists purely in the control and management planes and co-exists with the traditional data stacks as is illustrated in Figure 8. The CB interacts with the data stack by collecting operational metrics and by issuing control commands.

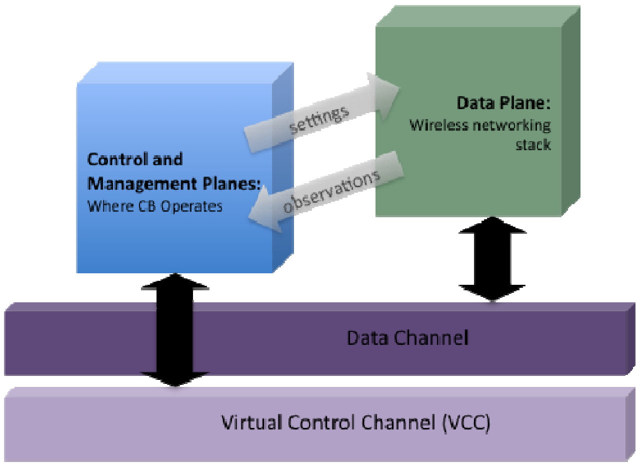


Fig. 8: Relationship between Connectivity Brokerage and the traditional wireless data-networking stacks.

To be generic, the CB architecture must have all the properties enumerated earlier in the sketch of the solution space: technology-agnostic, friendly to legacy technologies, extensible, scalable (over a broad range of dimensions), dynamic and adaptive, resilient and trustworthy. In addition, it should adhere to the lessons-learned guidelines, such as simplicity, clear abstractions and well-defined interfaces. We have adopted a strict object-oriented strategy with clear semantics to accomplish the aforementioned goals.

Connectivity Agents - Definition

The basic components of the CB architecture are the ***Connectivity Agents*** (in short ***CAgents***).

> *A CAgent is a generic object that represents a particular interest in the brokerage arena (to stay within the same terminology). It may represent the interests of a terminal (or a user), a wireless network, or a cluster of collaborating networks.*

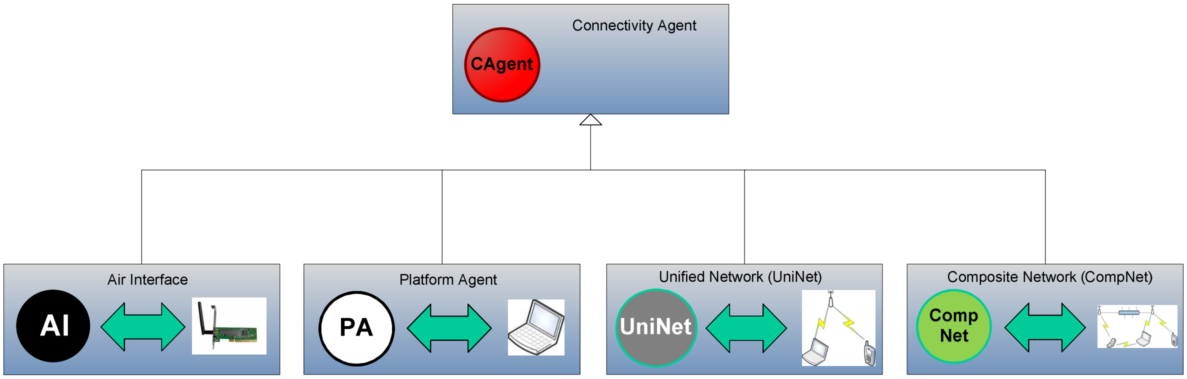


Fig. 9: The Connectivity Agent (CA) Object and its descendants (UML notation).

CAgents fulfill the goals of the CB within their control sphere while providing a uniform interface to adjacent CAgents, allowing for a seamless interaction between them.

From an execution perspective, CAgents can be classified as **Actors** within an Actor-based concurrent execution model.[1] For each interested party in the brokerage, a CAgent is created (distributed over all the nodes that comprise that party), interacting with cooperating CAgent through messages following a common protocol.

Each CAgent, independent of its nature, is characterized by a set of parameters, has a known state (divided into public and private sections), and supports a set of common functions. Following the object-oriented approach, all CAgents regardless of their interest inherit from a single class object. Fig. 9 shows the corresponding UML representation [UML00]. Depending upon the particular type of interest that is being represented, specialized subclasses can be defined, corresponding to the underlying abstracted technology. A number of such subclasses have been identified.

Connectivity Agents - Classes

Air Interface CAgent (AI) – abstracts a given wireless interface, and provides the needed interface and control knobs for it to work properly with other CAgents.

Example: AI CAgents exist for any wireless interface, such as 802.11 Wi-Fi, Bluetooth, Zigbee, 3G or any other (including emerging interfaces such as software-defined and cognitive radio). Typical parameters to be managed include channel selection, power level, coding, encryption, etc. Measurements to be observed may be RSSI, BER or the number of networks it could connect to.

[1] The **Actor Model** is a mathematical model of concurrent computation that treats "actors" as the universal primitives of concurrent digital computation: in response to a message that it receives, an actor can make local decisions, create more actors, send more messages, and determine how to respond to the next message received. The Actor model originated in 1973 and the most recent overview paper is by Carl Hewitt. It has been used both as a framework for a theoretical understanding of concurrency, and as the theoretical basis for several practical implementations of concurrent systems [Source: Wikipedia].

AI CAgents interact with Connectivity Agents of the Platform and UniNet classes.

Platform CAgent (PA) – represents the interests of a given (mobile/non-mobile) platform[2] within a CB controlled space. PA CAgent policies and behavior are strongly influenced by the preferences and privileges of the platform owner (such as the networks that s/he is allowed to connect).

Example: A PA CAgent may be an essential party in deciding which air interface to select for a requested data transmission/connection based on availability, utilization, QoS, and cost. Since a platform is typically associated with a particular user, the PA also plays a major role in adhering to or complying with security and access control policies.

A PA CAgent has a very strong supervisory association with the AI CAgents, installed on the platform.

Unified Network CAgent (UniNet) – represents a collection of AIs that adhere to a unified set of wireless communication rules or protocols, and that jointly pursue a unified optimization strategy. The most typical scenario for this would be a homogeneous network of similar AIs running under a common administration.

Example: Most wireless networks operational today fall under this class. Networks of cellular phones connected to a base station, Wi-Fi terminals under a single access point, and a Bluetooth network, all are UniNets. Emerging cooperative schemes such as mesh networks or collaborative MIMO are as well. The unifying theme is a common sense of purpose to form a network meeting certain goals/metrics. The UniNet CAgent may perform such tasks as selecting the most optimal channel, minimization of interference between terminals through slot allocation, determining access to the network, etc. Commonly observed metrics are network throughput, latency, overall Packet-Error Rate (PER), etc.

A UniNet CAgent interacts with compatible AI CAgents and with Composite Network CAgents (in case it is interested in cooperation.

Composite Network CAgent (CompNet) – represents a collection of UnitNets that are interested in cooperation or collaboration. In essence, it is the CompNet CAgent that truly enables the concept of connectivity brokerage. By leveraging a high-level understanding of connectivity resources and needs over multiple networks, the CompNet enables solutions that exceed what the UniNets on their own can accomplish. In addition, CompNets enable and support hierarchical structures and therefore improve the scalability of the system. In its simplest nature, a CompNet just shares information between its component networks; in its most complex form, it balances the diverse requirements of the networks and trades off between diverging cost functions and metrics, while adhering to dynamically changing policy rules.

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[2] A platform is defined here as any integrated terminal equipped with wireless interfaces. These may range from the very simple such as wireless sensor nodes, to Wi-Fi or Bluetooth equipped mobiles, cellular phones or Wi-Fi Access Points or 3G base stations.

Example: A CompNet unifying various interfering Wi-Fi Networks can in the simplest form share spectrum utilization data and networks loads; in a more sophisticated format, it can decide on channel selection and pass its decisions to the component networks. Even more sophisticated CompNets can jointly manage interfering Wi-Fi, BT and 802.15.4 (Zigbee) networks, competing for the 2.4 GHZ band. CompNets can also be used to negotiate between primary and secondary networks in cognitive radio systems.

CompNet CAgents interact with UniNets, as well as other CompNet CAgents representing other federated networks.

To summarize, a diagram illustrating the potential interaction between the different classes of Connectivity Agents is shown in Figure 10. Note that this diagram is purely functional, and does not indicate how the CAgents are mapped onto the actual implementation platform. This will be discussed in more detail later.

Connectivity Agents – Functions

A distinguishing feature of the CAgents is a common set of functions that each of them must support. This is perfectly in accordance with the object-oriented philosophy of the CB framework, in which each sub-class inherits the function definitions of the parent class. In the CAgent base class the functions are simple placeholders. As classes are refined, and as the CAgents are mapped onto the implementation platform, the role of the CAgent becomes more specific and one or more functions may dominate. For example, an access point may carry a more sophisticated optimization function than a client node. Some “dumb” nodes may not have any optimization at all.

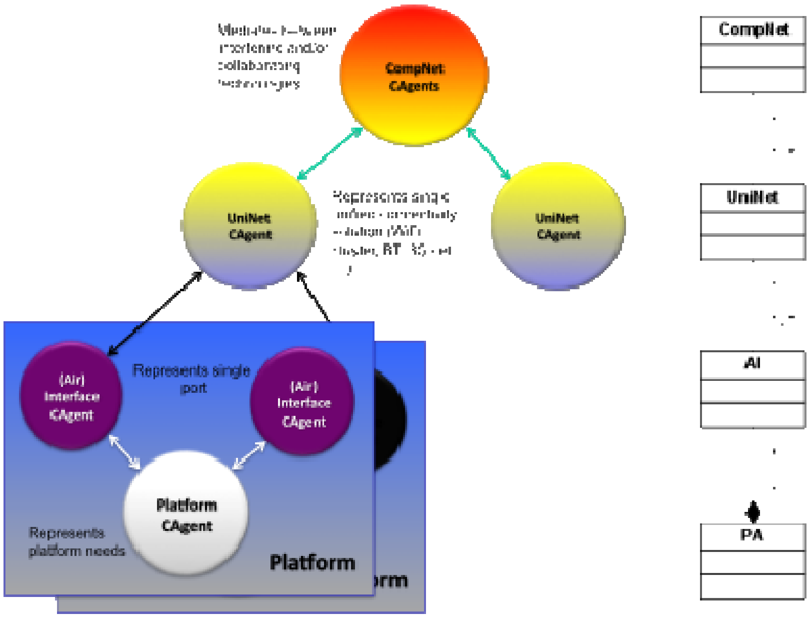

Fig. 10: CAgent classes and their interrelationship (with corresponding UML diagram).

From an evaluation of the basic control functions that each component in a generic wireless network must (more or less) perform, we have constructed a list of six fundamental functions essential to the CAgent concept. Figure 11 graphically presents an overview of these common functions. A detailed description follows below.

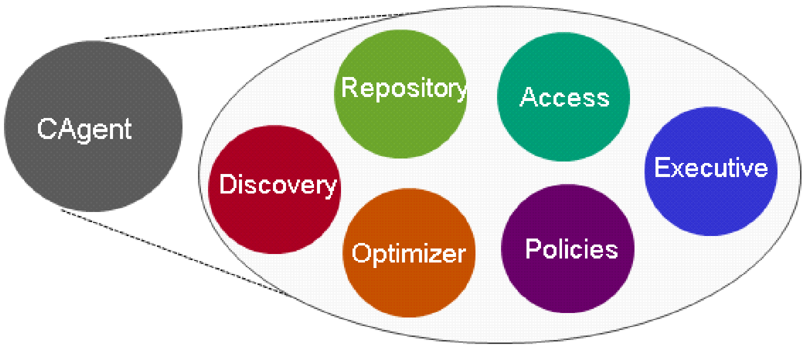

Fig. 11: A CAgent must support six fundamental functions.

- **Repository** – An essential requirement for effective cooperation and collaboration is that **CAgents make available (at least partially) to all interested parties information learned, decisions made, and current state.** These parties may be components that form the CAgent, or any other CAgent that interacts with it. This is enabled through a distributed repository structure. Each CAgent will publish part of its own repository to the global CB repository, making it public. The distributed global repository constructed in this manner is the backbone of the CB framework and the fundamental component that enables cooperation and dynamic information exchange among wireless technologies.

> **Example**: A wireless network may want to publish its average workload, its observed Packet-Error-Ratio, as well as the specific channel it occupies. An Air Interface can share its power level, observed RSSI, as well as the names of the networks it observed.

- **Discovery** – A cornerstone of the CB concept is the capability to actively **learn the properties of the environment**. The discovery function extracts and filters useful information from a massive amount of data, which can be collected from different levels and layers of the wireless systems. The resulting information is posted in the repository.

> **Example:** The AI discovery function is often involved with learning the radio level properties such as spectrum usage or discovery of compatible neighbor technologies. Discovery functions at the UniNet and CompNet levels are more involved with learning network-level statistics or data.

- **Optimization** – The obtained information can be used to optimally configure the system so that performance goals or other criteria are met within the boundaries of the guiding rules and policies. The required optimizations are often implemented in a distributed or semi-distributed fashion and therefore each CAgent should be able to engage in a distributed optimization strategy.

> **Example:** An AirInterface chooses the UniNet to join as a result of an optimization process that is done with respect to discovered information, access control, and policies. A CompNet optimization strategy might be to mitigate the negative effects that the involved UniNet CAgents have on each other. The resulting action may depend on the learned information and policy constraints.

- **Execution** – The outcomes of the optimization process need to be conveyed to the interested parties and executed in a reliable and equitable fashion. Execution of decisions over distributed systems might require relatively complex coordinated transactions. This is why this is a fundamental function for every Connectivity Agent.

Example: A UniNet that decides to use a different frequency will rely on the executive function in order to ensure the command is performed in a reliable fashion over the complete network.

- **Access control** – How information is gathered and disseminated through the system and who is allowed to actively participate in the automation and management process is subject to rules and trust mechanisms. Cooperative systems can become a prime target of malicious attackers and the security and access control aspects need to be explicitly addressed. Authentication of the different CAgents as well as repository data access control and association processes are part of this function.

Example: Only AirInterfaces that can associate with a network (such as set by a single Wi-Fi access point) can typically have access to the internal information of that network. Based on the authentication process and the access privileges, some of that information can be broadcasted to a broader range of interested parties.

- **Policy Support** – Policies set the boundaries and ground rules of the optimization processes. In contrast to current practice (in which the policy is cast in stone in advance), the policies may vary dynamically, and the networks should be able to adapt these variations. This is a truly innovative feature introduced by the CB concept. It is an essential element of the “brokerage” model.

Examples: A policy within a CompNet may be not much more than a set of weighting parameters, helping to set priorities over different wireless data services with competing needs. These policies can be set by the system operator, or may be defined by regulators. As an example of a dynamic policy change, priorities may be redefined in the case of emergency or network overload. For a mobile terminal, the policy may be set by the user to express his/her preference between different network choices.

In principle, every wireless technology deployed today intrinsically includes some if not all of the above defined functions. However, none of this is exposed to other technologies that may wish to interact. The CB software architecture provides the means to do just that. The CAgent Object model provides for a clear and well-defined separation of functionality. It also helps identify what data and state to make public and what to keep private.[3]

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[3] An attentive reader may observe that the described functions partially map into the “manager” objects of the IEEE P1900.4 standard. However, the main difference between the CB and 1900.4 is how the functions are grouped and structured. For instance, the repository function is distributed over multiple managers, as is discovery. The policy function is an integral part of the NMR. In the CB architecture, each CAgent function addresses one unique aspect. We believe that this leads to a more generic, transparent, and scalable architecture.

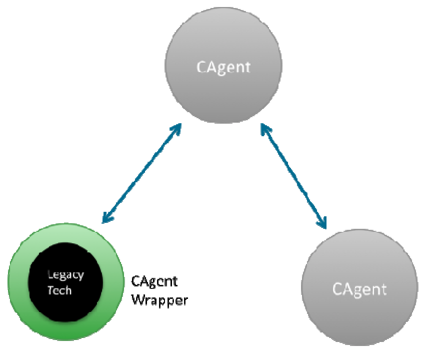

Fig. 12: Importing legacy technology with wrappers.

Obviously, rewriting existing implementations of legacy wireless networks and interfaces is not a real option. Yet, **the CAgent model with its object-oriented underpinning[4] makes it possible to develop wrapper layers around the legacy systems**, so that they behave as full-fledged CAgents in their interactions with other systems (Figure 12). In its simplest form, these wrappers may just support the inter-CAgent message passing strategy and make some data and state of the legacy system available to interested parties. In more complex forms, it would expose and allow full interaction with all the functions identified above. This approach allows legacy systems to get partial or full benefit from the cooperative and collaborative nature of the CB framework. It goes without saying that new implementations, constructed from scratch with the CB model in mind, have the potential of reaping larger benefits.

Connectivity Agents – Communication

As stated earlier, the CB framework is structured around an actor-based concurrent execution model, in which CAgents interact with each other using messages. This implies that the CAgents are capable of communicating with each other. This is a non-trivial assumption. Depending upon their nature, CAgents can be *centralized* or *distributed* across multiple platforms. For instance, AI and PA CAgents normally (but not necessarily) reside on a single node, while UniNet and CompNet CAgents in general benefit from a distributed instantiation and may be spread over all the nodes they comprise. It is obvious that intentional cooperation between CAgents that have no means of communication (in other words, that reside in non-connecting network islands) is impossible.

Providing seamless and uniform communication between CAgents that reside on drastically different networks is a non-trivial but essential endeavor. One solution would be to create an explicit control channel, dedicated to the interchange of control information. This is the approach that some have advocated for the deployment of cognitive radio networks. The disadvantage of this approach is that it does not work with legacy nodes, and that it may require the addition of special hardware, especially when the data channels of the participating networks are in different frequency bands.

[4] An implicit assumption of any object-oriented modeling approach is that objects offer a clear abstraction, come with well-defined functionalities, and provide unambiguous interfaces.

In reality however, networks and network nodes are rarely completely isolated. The combined connection, bridging and routing capabilities of the network technologies actually helps to ensure that most nodes are somehow connected to one another. The fact that access points and base stations are connected to the wired network (Internet) is of substantial help. We therefore conclude that the communication of control information between various CAgents is intrinsically possible, as long as the constituent network graphs are connected.

This observation helps to construct an abstraction of communication backplane, called the **Virtual Control Channel (or VCC),** which hides the detail of how information messages are routed between nodes. All CAgents communicate with each other over the VCC using a uniform interface protocol, as was illustrated earlier in Figure 8. Notice that the path control information follows may be quite different from the road the associated data path takes. The VCC is established and maintained as a service to CAgent objects, as will be discussed later.

The VCC Communication Abstraction:

With the VCC abstraction, CAgents can communicate seamlessly with one another, ignoring the details of how the data is delivered, and the precise nature and location of the communication partner(s). In the actor model, agents interact with each other by exchanging messages. These messages serve to either share information available in the public repository of the CAgents (such as measurements obtained during discovery), or to change that information (such as adjusting the parameter settings). While the CB framework keeps the nature of the message payload open, it does define the overall format as outlined in the footnote below.[5] In general, messages between CAgents

The timeliness of the information in the repository is very important. For the CB to do meaningful work, it is essential that the data is fresh. This means that a time-stamp must be part of the messaging mechanism. Unfortunately, different CAgents work on vastly different timescales (For example, network establishment versus physical layer measurements), and the requirements of timing resolution and accuracy may vary greatly. This observation makes it clear that the CB needs a distributed timing synchronization service, providing resolution and accuracy as needed for players involved.

[5] All messages passing through the VCC adhere to the following format:

- Each message has a unique identifier.
- A message always has a source and a target field. These could identify a CAgent, or a set or class of CAgents. However, the target could also contain a particular type of information. To support this, it is necessary that each CAgent have a unique name within its local domain of interest (that is, unique with respect to its siblings). For Instance, the name of a Wi-Fi UniNet could be its SSID (e.g. “EECS-SECURE”). When traversing hierarchy levels (that is, crossing more than one hop in the CAgent connectivity graph), the uniqueness of the name can be guaranteed through concatenations. For instance, the name of the Wi-Fi AirInterface on my laptop could be “Tantalus.Wi-Fi-bg”.

There exist many different message delivery mechanisms. While they are all functionally equivalent, their properties are quite different in terms of ease of use, addressing, timeliness of delivery, etc. The simplest is a database-inspired approach that supports just two types of messages: get() and set(). Another approach that has gained a lot of support in the networking community is the **publish-subscribe mechanism**, which has the advantage of working very well in situations with a lot of broadcast traffic (as is the case in the CB). Hence, we have adopted the latter as the **premier messaging approach in our framework**.

Virtual Control Channel as a Service:

The establishment and maintenance of the VCC is crucial to CB operation. As noted earlier, the idea of providing explicit channel(s) and radios for the purpose of control is incompatible with legacy technologies and potentially requires additional hardware. A more generic solution is inspired by the observation that most of the current wireless platforms are only within a few hops of a global wired connection. Hence, a fully connected control network can be constructed by using wireless links in combination with the dense and seamless connectivity of the wired backplane. This most often eliminates the need for dedicated wireless control channels. In fact, control channels can be dynamically mapped to a very heterogeneous set of links, and might pass through boundaries where data traffic is not allowed (we assume that control traffic is negligible compared to data traffic). The establishment and control of the VCC requires an intricate interplay between the CAgents (who perform the early discovery) and the Data Plane, in which the control connections are established.

Observation: In setting up the VCC connectivity, the most challenging problem is setting up the necessary communication links between heterogeneous networks, or, in other words, the links between UniNet and CompNet CAgents and CompNet to CompNet, as direct channels between those typically do not exist. Neighboring AirInterface, Platform, and UniNet CAgents typically reside on the same hardware platform, or belong to a single homogeneous network.

A common way to establish a common functionality available to all is to establish a “service”. A service can be defined as "a mechanism to enable access to one or more capabilities, where the access is provided using a prescribed interface and is exercised consistent with constraints and policies as specified by the service description." [Definition: Aston]. This requires that all nodes involved in the CB framework support a common functionality. It is fair to say that the establishment of the VCC alone can be considered as a paradigm shift in the wireless networking community (similar functions have long been established in the wired world).

Connectivity Brokerage – How it Maps onto the Physical Implementation Platform

So far, we have treated the CAgents as purely functional objects, and have left the question open on how this functionality maps onto the mobile and non-mobile platforms within the space of interest. Among the CAgents, the AI and PA naturally map onto the mobile platforms (and interfaces) they represent, and hence are generally realized in a non-distributed fashion. The UniNet and CompNet CAgents, on the other hand, most likely benefit from a distributed implementation. In fact, as long as the CAgents can provide the functionality expected from them, and are capable or presenting the necessary interfaces to the rest of the CB infrastructure, whether they are implemented in a centralized or distributed fashion is truly a secondary issue. Nevertheless, latency, implementation or reliability concerns may cause the solution to converge to either of the two extremes, or to a hierarchical solution in-between.

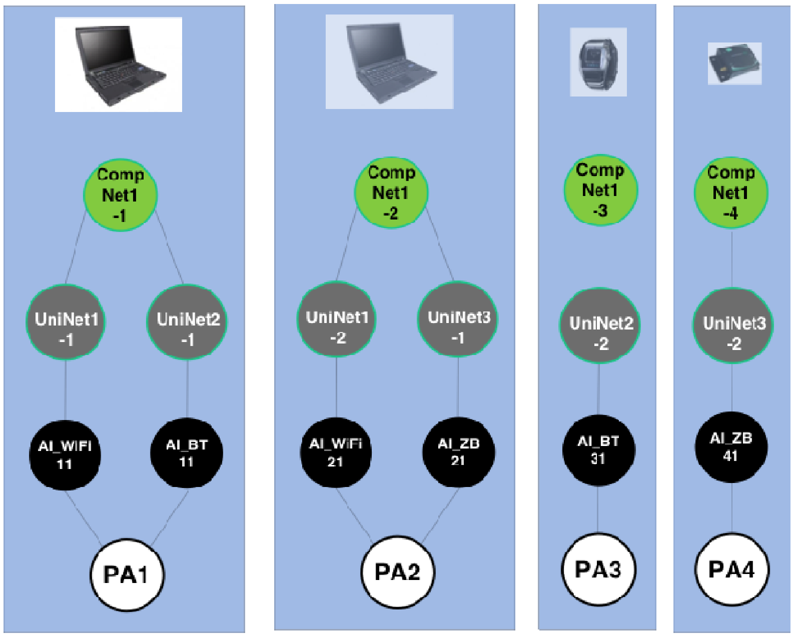

Figure 13. Mapping of CB functionality on the distributed communication platform.

As an example, Figure 13 demonstrates one possible strategy for mapping and implementing the CAgents on a distributed platform. In this scenario, each (distributed) CAgent has a representative instantiation on any (mobile or fixed) device that has an association with it. For instance, CompNet1 has four instantiations that together support the needed functionality. UniNet1, UniNet2 and UniNet3 each have two representative instantiations. Observe that these instantiations do not have to be (and most often are not) identical in capabilities. As an example, the Wi-Fi CAgent instance running on the Access Point clearly has a different set of functions compared to the instances of the CAgent on the mobile devices.

Connectivity Brokerage – How it Emerges and Evolves.

To understand how the CB functionality emerges, evolves and adapts under changing environmental conditions, let us consider the simple example of an indoor office environment and assume that that environment is empty at the start. In this scenario, we will examine how multiple heterogeneous networks are established and together will form a single collaborative CompNet. For the sake of simplicity, we assume each network uses a star topology with a single access point.

Every node (platform) that is deployed initiates the AI CAgents corresponding to its wireless interfaces. Upon installation, the access point will also initiate the appropriate UniNet. *This is guaranteed to be the first one of its type*. This AP is now ready to service platforms with the right privileges – which can join the established UniNet. The VCC service, running in the background, uses the obtained information to extend the scope of the VCC network (bridging for instance the wireless nodes to the wired network).

The next step for the AP is to decide whether an instantiation of a CompNet object exists within the given environment. *If the AP concludes that there is no such instantiation, it instantiates one itself, such* *that emerging networks can identify and associate with it*. The VCC is an essential element in the detection of existing CompNets with which the AP can associate.

After the AP detects the existence of a compatible CompNet, the association process begins. We assume the corresponding access point has the right privileges for this association to be successful. Through this process the VCC will be extended such that the new UniNet is trivially accessible by the CompNet and vice versa. In addition the UniNet and CompNet repositories will be updated.

Observe that the creation of and association with UniNets and CompNets is a continuous process, allowing for networks to be dynamically reshaped and restructured based on the availability of nodes and environmental conditions.

5. Connectivity Brokerage Use Cases

Connectivity Brokerage is intended to be a general control/management framework that should cover a broad spectrum of existing and future collaborative wireless paradigms. However, the potential impact of the CB depends greatly on the available mechanisms offered within a use-case scenario. For example, while the CB can enable improved decision-making regarding seamless handover, the networking stack still needs to be able to perform the needed handover procedures.

In the following, we examine **several innovative and sometimes futuristic cooperative/collaborative solutions**, and clarify how CB framework enables them.

A. Cooperative Interference Mitigation for Homogeneous and Heterogeneous Wireless Networks (Heterogeneous Dynamic Resource Allocation)

Over the past few years, a new set of solutions has been introduced and published that all attempt to improve the performance of managed wireless networks (particularly enterprise 802.11 based networks) by minimizing the inter-network interference effects through *coordinated resource allocation* [MIS07] [ROZ07][KAU07].

Most of these proposals attempt to keep the required modifications to a minimum in order to increase the chance of adoption. For example, the solution proposed by [MIS06] is the first to include the observations obtained by the client nodes, by having them perform periodic site-survey operations. All earlier similar solutions had only considered gathering observations from the access points. These observations can be used to construct a conflict graph between the networks and use the estimated conflicts as an input to the optimization algorithms.

[ROZ07] takes an extra step and fuses the client observations with the estimated transmit and receive rates of the individual nodes in order to achieve a better estimate of the conflicts among the networks. As one could expect, the authors demonstrate that fusing the traffic load information is mostly useful when hotspots exist and loads are non-uniform.

If the CB framework was available at the time of inception of these projects, the designers could have avoided the design and implementation of new specialized control and signaling frameworks. The CB abstracts the different terminals and networks through the CAgent objects and provides the needed interfaces (Figure 14). The *discovery* function supported by CAgents can gather and filter the useful information and write it to the *repository*. In [MIS06] and [ROZ07], optimizations are done in a centralized fashion. The CB also supports distributed *optimization* schemes if necessary. At last, the *executive* function carries the executive commands to the execution points and guarantees their enforcement. It is apparent that the CB framework fits very well with the control system requirements of such optimization schemes.

In similar ways, the Connectivity Brokerage can support resource allocation and interference mitigation over heterogeneous wireless networks. The distinctive challenge of heterogeneous networks lies in network discovery and modeling of interference effects. For instance, in enterprise WiFi networks, nodes can capture the packets from interfering radios, which is not the case for heterogeneous networks. The estimation of useful interference metrics between heterogeneous wireless networks is the subject of active research.

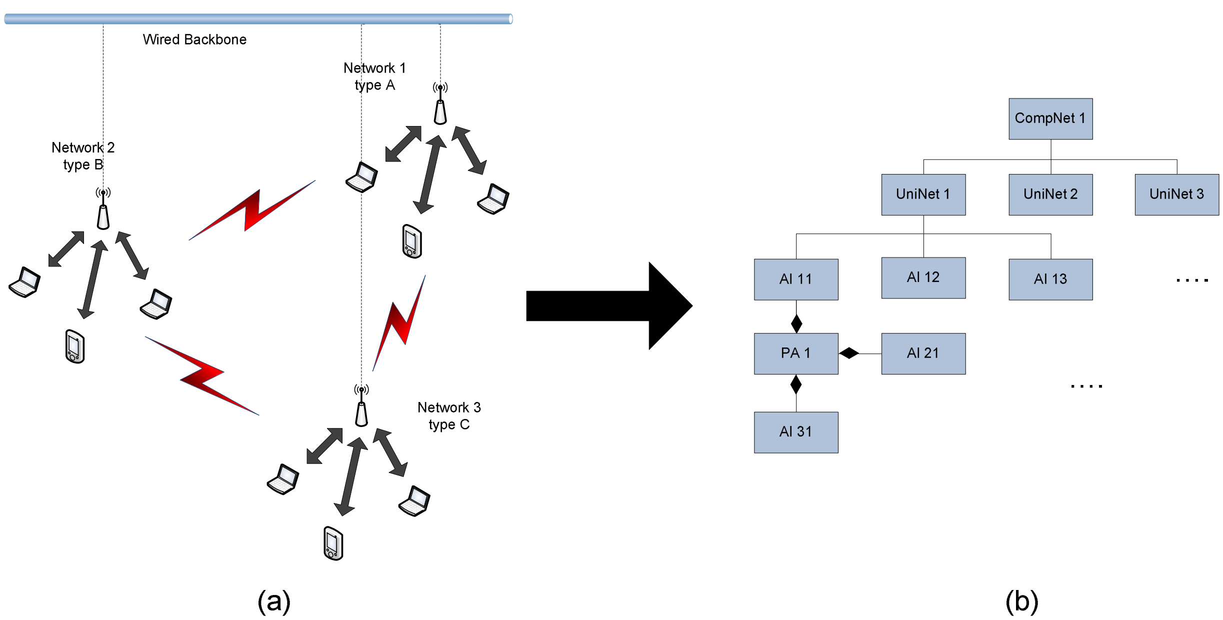

Fig. 14. Use Case 1 –Cooperative Interference Mitigation between Heterogeneous Networks.[6]
(a) Network configuration; (b) UML diagram of CAgents involved.

B. Interference Cancellation and Distributed MIMO

Cancellation is another interference management paradigm. Consider wireless networks that are close to each other, but are individually managed and hence interfere with each other's transmissions. In

[6] While the example shows the networks connected to a wired backhaul, this is by no means a necessity in the CB environment. However, having the backhaul simplifies the set up of the VCC.

contrast to the first use-case (interference avoidance), the implementation of *interference cancellation* might require extensive modifications at the physical layer, such as the introduction of special encoders and decoders. By its very nature, the Connectivity Broker does not engage with data processing operations in the physical layer. Hence, it may seem that the CB has no role to play in this use case. This is far from true though, as the CB plays a number of crucial roles in various cooperative interference cancellation schemes. Obviously, each of these scenarios assumes that the wireless air interfaces involved are equipped with the necessary physical-layer capabilities.

- Any receiver engaging in *interference cancellation* must be capable of decoding multiple streams of data simultaneously. No changes are needed at the transmitter side. To that end, the receivers need to know the codebooks used by the interfering users, as well as information on the state of the interfering channels. The Connectivity Brokerage provides the backend platform to support this (Figure 15): once the UniNet CAgents of the two wireless networks agree to cooperate and initiate a CompNet CAgent, each user's codebook and the training pilot sequence can be written into the repository. As such, this information is now available to the interested receivers. Interference cancellation performs particularly well (compared to pure orthogonalization, or by treating interference as noise) when the interference strength is larger than or equal to the desired signal. When the interference is weak, receivers fare just as well by treating the interference as simple noise. The Connectivity Brokerage can also help the receiver decide whether it should decode the interference or not, based on measurements of the direct and interfering channel strengths as written in the repository.
- To implement *partial interference cancellation*, the decoder at the receiver has to support interference cancellation (see above). In addition, the encoder at the transmitter side has to provide *superposition coding*. Under this scenario, the CB must not only provide codebooks and training pilot sequence information to all receivers, but also must convey the interfering channel state information to the *transmitters* to help them determine the proper power split [ETW08]. For each transmitter, two codes are employed: common ones, which serve all receivers, and private ones, which are aimed only at its own receiver. The idea is to decode and cancel part of the interference (using the common codes). Theoretical results show that this is a near-optimal way to manage interference in the two-transmitter-two-receiver setting [ETW08].
- If the two access points are connected through infrastructure backhaul networks (e.g., Ethernet cables), *distributed MIMO schemes* may be employed. The idea of *distributed MIMO* is to combine two access points so that encoding/decoding can be done jointly. In this way, interference can be either nulled out via pre-coding in the downlink scenario, or cancelled via joint decoding in the uplink scenario. Theory [WT09, WT10] shows that, facing different amounts of interference, the same amount of backhaul results in different marginal gains in capacity. Note again that the Connectivity Brokerage plays no role in the physical layer operation, i.e., joint encoding and decoding. Instead, the CB stands at a higher level to coordinate the limited backhaul links so that their utilization is efficient. Once the CompNet CAgent sitting on top of the two UniNet CAgents decides to form a distribute MIMO system where the cooperation become very close, the CompNet CAgent will merge the two UniNet CAgents into a single UniNet. The CB can also take other factors into account, including fairness, security, etc., to optimally assign the usage of backhauls.

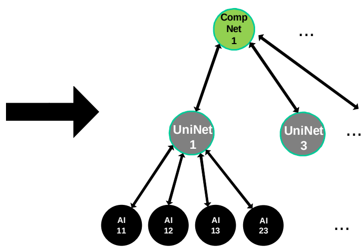

Fig.15. Use Case 2 – Networks 1 and 2 detect that there is opportunity for joint interference cancellation. Hence it would be opportune for the corresponding UniNet CAgents to merge into a single UniNet. The CompNet not only coordinates the opportunity detection and the merging processes, but also oversees the distribution of the backhaul capacity between this UniNet and other networks.

C. Seamless Horizontal and Vertical Handoff

Enabling seamless handoff and dynamic traffic distribution over heterogeneous wireless interfaces is a very active area of research in the wireless arena. The Connectivity Brokerage can help to achieve seamless horizontal handoff between homogeneous networks and vertical handoff between heterogeneous networks by providing pertinent information to decision-making CAgents, and by enabling various global optimization strategies (Figure 16). “Media Independent Handover” [INT09] proposes a possible solution for the vertical handover problem between heterogeneous networks, including GSM, WCDMA, WiMAX, WiFi and cdma2000. With the CB architecture, this connectivity roadmap can be further extended to include uncoordinated bands and cognitive radios. The Connectivity Brokerage, sitting at a higher level, can help existing handoff technologies make better decisions and achieve seamless transitions.

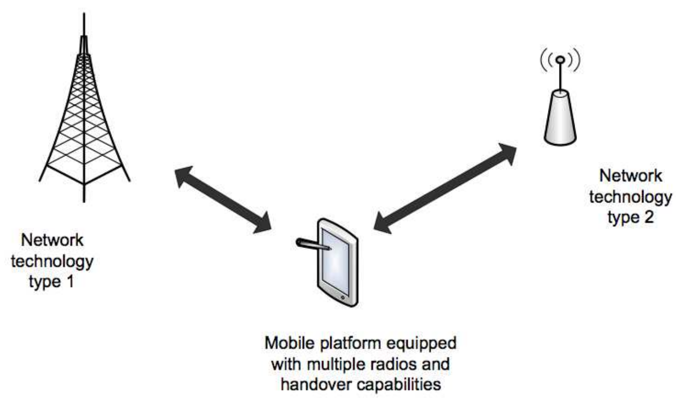

Figure 16. Use Case 3 – Selection of the appropriate network requires coordination and optimization across network boundaries. The CB framework enables access to new resources, and provides extra information-exchange and optimization capabilities.

D. Collaborative Cross-Operator Traffic Delivery

The CB can enable homogeneous and heterogeneous wireless networks to provide dynamic load balancing, moving traffic from one to another based on available resources and costs. In today wireless systems, it often happens that a platform or network can achieve better (or cheaper) connectivity if it is not blocked from accessing resources of neighboring networks due to policy, security or cross-domain restrictions. The CB should enable lifting of these barriers if the operators are willing.

For such schemes, the information gathered by the *discovery* function will be crucial in identifying the potential opportunities. In this way two CAgents in neighboring networks can decide when they will benefit by constructing a higher-level composite network and providing traffic delivery services to each other, informed by the proper *Policies*. In addition the *Access Control* and *Optimization* functionality will help to decide if interfacing and delivering the traffic through a specific neighbor platform or network is not a security threat. At the end the *Executive* function will ensure the decisions are enforced at the execution points.

Use-cases C and D are quite inter-related, although the challenges they address are very distinguishable. In the handoff use-case the system's challenge is to dynamically (and hopefully seamlessly) change the traffic distribution among the accessible connectivity solutions, while the Collaborative Traffic Delivery is more concerned with expanding the access boundaries.

6. What's Next?

Earlier, we quoted "broad participation" as one of the guidelines essential for the creation of a truly universal framework. This white paper is our invitation to the broad community to get involved in this exciting endeavor that may transform how wireless systems operate and are operated. We truly are looking for a broad range of input and feedback. Our intention is to organize a small e-workshop in the near future with interested participants from different corners of the world. We also plan to actively engage with the IEEE P1900.4 steering committee to explore convergence opportunities.

In the meantime, we are moving forward on the realization of a small test bed in Berkeley demonstrating the usage of the Connectivity Brokerage in the use cases described in the text. This test bed is built on publicly available hardware and software. A description can be found in Appendix A. Again following the guidelines for successful frameworks, all results are completely open. The CB team also plans to engage with the European IP CREW (Cognitive Radio Experimentation World) activity, which attempts to build a pan-European heterogeneous test bed for cognitive radio in its broadest sense.

Our ultimate hope is that the set of ideas outlined in this paper may help ferment a wave of new thinking on how to most effectively use treasured spectrum and how this may help sustain the growth in wireless connectivity over the next decades, opening the door for a broad range of new applications for the good of mankind. To do so will by necessity also require the engagement of other interested parties such as policy makers, regulators, and socio-economic visionaries.

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Appendix A: Prototype CB Test-bed

To illustrate some of the concepts introduced in this white paper, we describe the use of the CB architecture over two 802.11g WLAN networks that have the potential to strongly interfere with each other. Each network has one access point (AP) and a number of clients and operates in managed mode.

We use off the shelve equipment to implement this test-bed. To add sensing capabilities to the WLAN networks we use USRP [ETT10] platforms, which are programmed to measure the energy levels in the 2.4Ghz ISM band (this information will be used by the discovery function of the AI CAgents).

Fig A.1 shows the test-bed object diagram. The WLAN networks are represented by the corresponding UniNet CAgents. In practice, these CAgents are distributed across the associated nodes. Since the two networks overlap in frequency and space, a CompNet CAgent is instantiated to enable coordination/collaboration between these UniNets. The AI CAgents of the individual nodes have been associated with the UniNets under the PAs' supervision.

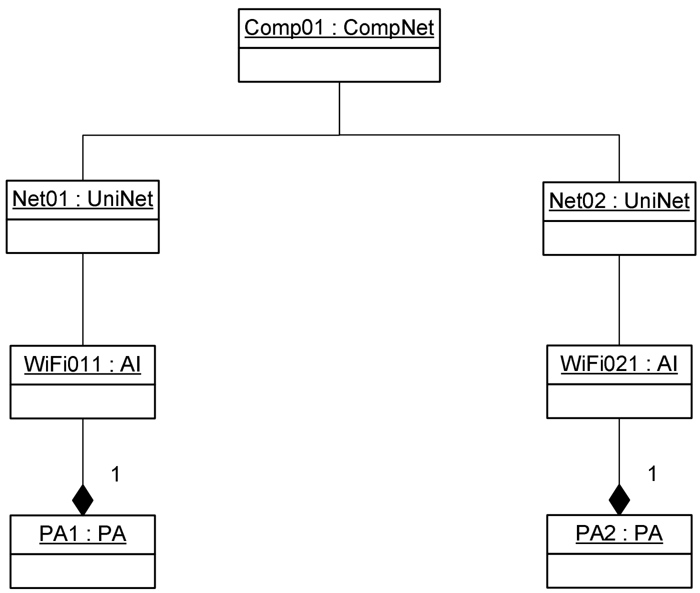

Figure A.1: UML object diagram of the CB test bed

This simple set-up already unearths a rich set of brokerage opportunities. Yet even a simple coordination technique goes a long way towards exposing the power of the formalism. In the example detailed below, the CB enables the two networks to continue operating close to optimal in terms of the interference they experience from the environment. For simplicity, let us assume that the two networks will only operate in non-overlapping 802.11g channels (1, 6 and 11). Each UniNet computes an ordered preference list of the available channels in terms of the least ambient interference at the access point and the clients. Adequate information about the ambient interference is obtained by the "discovery" function of the UniNets.

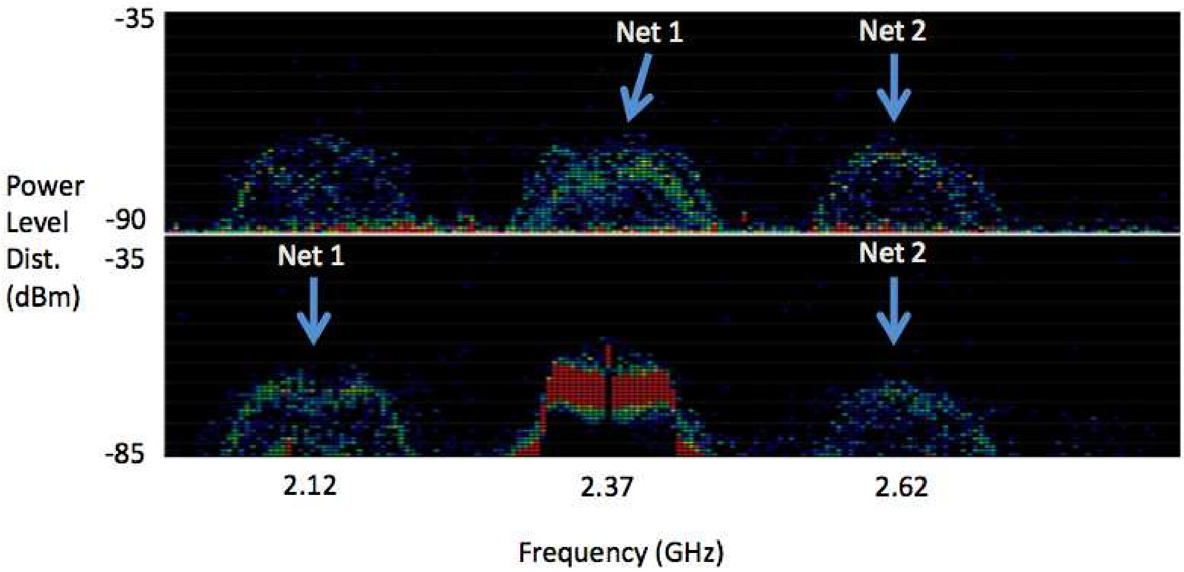

Fig A.2: Spectrum activity in 2.4 GHz ISM band before and after the jamming operation. The horizontal axis is the frequency and the vertical axis is the measured power in dBm.

The CompNet uses the channel preference calculated by individual UniNet CAgents to assign operating channels to the two networks. In cases where both wish to use the same channel, preference is given (by policy) to the network with the largest traffic load (which is also stored in the repository). The dynamic nature of the CB process is demonstrated by introducing a jammer into the environment and observing the reaction of the networks. Fig. A.2 shows a picture of the spectral map of the ISM band before and after jamming (captured by a spectrum analyzer). The first plot shows a histogram of spectrum activity before the jammer starts. UniNets Net1 and Net2 are operating in Channels 6 and 11, respectively (a setting which is already a result of CB coordination). When the jammer enters channel 6, the UniNets sense interference, alter their channel preferences, and report the changes to the CompNet via the repository.

The CompNet then requests Net1 to move to Channel 1 (second plot in Fig. A.2). While this scenario could easily be implemented in an ad-hoc fashion, the CB concept allows for a scalable and modular realization. New policies, optimization mechanisms, and collaboration schemes can be easily and dynamically adopted by this structure.