MOBILE FLEXIBLE NETWORKS: THE CHALLENGES AHEAD

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ABSTRACT

The general framework of Mobile Flexible Networks is to design self-organizing secure networks where terminals and base stations interact and self-adapt in an intelligent manner without the need of a central controller (or with the right amount of regulation...just enough to let the agents in the network exploit fully the degrees of freedom). Of course, the design depends on the mobility pattern and delay tolerance as in highly mobile environments, exchange of control signaling bears a huge cost whereas for fixed (non-mobile) networks, the designer can dedicate a fraction of the rate (which is negligible in terms of overhead) to optimize the system. One of the big challenges is to find how to optimally split the intelligence between cognitive terminals and cognitive networks. In this paper, we discuss the challenges ahead and provide some research directions to develop the theoretical foundations of these networks.

I. INTRODUCTION

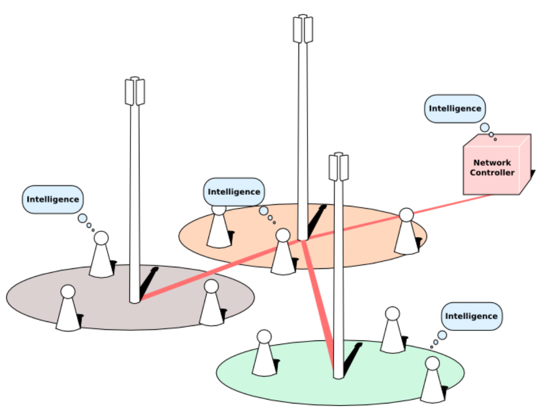
Imagine a highway which dynamically switches the number of dedicated downstream and upstream lanes according to the observed car traffic. The highway would go from two to three lanes if the traffic is dense. It would also signal to the different car drivers, depending on their needs, changes in their directions in order to ease the traffic process. It would coordinate for example with other highways the traffic lights for scheduling the cars accordingly. It could also transform the road material (from smooth to harsh), to force the users to reduce their speed depending on the weather conditions for security reasons. Finally, in the case of electrical cars, the highway could absorb the kinetic energy of high speed cars to recharge other slow cars (in need of energy) on the highway through contact of the wheels with the road. This would reduce drastically the infrastructure cost of gas stations. In other words, it would flexibly adapt according to the external circumstances in order to absorb the traffic without the need of additional expensive infrastructures. Change now the highway into a telecommunication network and the car users into terminals and you will get what is known as Mobile Flexible Networks. One can immediately see the potential of such networks, able to let information and energy [1] flow in a transparent manner. In some sense, the network texture changes opportunistically.

Mobile Flexible Networks [2] is a disruptive technology targeting very high spectral efficiencies beyond the actual known limits. Indeed, in the cellular wireless arena, engineers frequently stumble on the scalability problem that can be summarized by the following sentence: ”As the number of cells in the network increases, interference becomes the bottleneck”. As networks become more and more dense, classical techniques based on frequency and space reuse or power control are not be able to cope with interference due the increasing number of terminals. On the contrary, Mobile Flexible Networks do not consider wireless resources as a ”cake to be shared” among users but take benefit of the high number of interacting devices to increase the spectral efficiency frontier. In some sense, more devices represent more opportunities to schedule information which enhances the global throughput. In fact, interference is considered as an opportunity rather than a drawback by exploiting intelligently the degrees of freedom of wireless communications.

- Space: MIMO (Multiple Input Multiple Output) Networks coordinate the transmission of various base stations and increase the operating signal to noise ratio (SNR) point of the network. It provides the natural multiplexing and diversity gain of MIMO systems (effective at high SNR) and a linear scaling of the capacity with the number of cooperating base stations. Hence, in theory, the only limiting factor for increasing the spectral efficiency is the number of base stations. The technology, adequate for dense networks, relies on sophisticated tools of dirty paper coding and cooperative Beam-forming.
- Frequency/Time: Cognitive networks coordinate the transmission over various bands of frequencies by exploiting the vacant bands in idle periods. It requires

antennas able to work in a large range of bandwidth for sensing the different signals in the network. The high density of base stations (by reducing the cell size) enables the use of higher frequencies (for which the path loss increases).
- User: Opportunistic networks coordinate the transmission to different users in the network, by scheduling intelligently the information to users in good Signal to Noise Ratio conditions. It turns out that as the number of users increase, the spectral efficiency of opportunistic network increases, as the probability of having a user with a good channel increases with the number of users. These techniques are already deployed in actual systems but will be more advantageous in future highly dense environments.

Mobile Flexible Networks will be at the end self-organizing secure networks where terminals and base stations interact and self-adapt in an intelligent manner with only a limited amount of regulation (enough to let the terminals/base stations in the network exploit fully the degrees of freedom), being in some sense a bridge between the full centralized and fully decentralized network approaches. With the multiplicity of standards that are appearing (UMTS, WiFi, WiMAX, LTE), Mobile Flexible Networks will become more and more necessary. They will have additional features to sense the different technologies, the energy consumption of the terminals and reconfigure (changing from an LTE to UMTS base station if UMTS terminals are present) to adapt to the standards or services to be delivered at a given time.



In the following sections, we will discuss in details the concepts behind Mobile Flexible Networks as well as the theoretical tools involved in the design of the networks.

II. Breaking the Spectral Efficiency Barrier

II-A. From b/s/Hz...

Before introducing the concept of Mobile Flexible Networks, let us first give a brief description of the well known technologies at the moment. In the case of wireless communications, several generation of standards have been developed going from 2G (known as GSM) to 3G (known as UMTS) and now 4G (with the LTE/WI-MAX era). In each case, specific access schemes were use such as TDMA (Time Division Multiple Access for GSM) to CDMA (Code Division Multiple Access) and FDMA/OFDMA (Orthogonal Frequency Division Multiplexing) for Wi-MAX/LTE.

To understand the differences between these different access schemes, let us give a well known example. Suppose that a great number of couples within a room would like to communicate. Each member of the couple would like to talk to its partner and is not interested in what others are saying. In order to make that happen, several possibilities are offered to us.

Let us first make the analogy with the case of FDMA (Frequency Division Multiple Access or its advanced version known as OFDM). This system can be represented by walls being built within the room, providing small rooms (the construction of the walls has a cost which corresponds to the spectrum bought). Hence, each couple can go in a small room and can communicate without being disturbed by the other couples. The differences between FDMA and OFDMA lie in the fact that in the latter case, one can build very thin walls (thanks in fact to the use of digital Fourier modulator) which optimizes the space used.

In the case of TDMA, all the couples would be in the same room. Each couple would talk a certain amount of time in the big room, one couple after the other. Hence, a delay would be incurred depending on the number of couples and the time granted to each of them.

In the case of CDMA, all the couples would be in the same room and talk all the time. However, each couple would talk a different language and would not understand other languages. The code here is the language which is specific to each couple. The language appears here as a filter as for example, the French couple would not be able to understand the German or the neighboring Chinese couple. For each couples, foreign languages would be considered as background noise. This technique has of course actual limits as one can not add couples in the room whenever the noise generated becomes too important for any reliable discussion (or that no more new languages are available).

II-B. ...to b/s/Hz/m^2

Before providing the analogy with couples for Mobile Flexible Networks, let us go back to the fundamentals of Wireless communications. Historically, in order to serve the users, service providers have deployed base stations. It immediately appeared that to better serve the users, a dense network of base stations was needed but at the same time, this would generate harmful interference. In order to alleviate this problem and reduce interference, virtual walls (with a non-negligible cost...the different frequency bands bought for each technology) were built. Unfortunately, interference is a misleading word especially when it is not natural but generated by the network. Mobile Flexible Networks consider on the contrary interference as a useful signal that can be exploited and build bridges (instead of walls) between the systems. Hence, more interference means more virtual cables that one can use to transmit information towards the users. The highways are in fact created by the users which are present in the system. In theory, these networks have no capacity limit beside the space constraint but require intelligent devices to acquire the knowledge on the topology at each instant (known as Channel State Information at the transmitter and receiver). The shift from b/s/Hz to b/s/hz/m^2 in terms of spectral efficiency is instrumental in the definition of these networks. This provides a unique opportunity to trade spectrum for space and break the spectral efficiency barrier.

As far as our previous example is concerned, if the people are smart enough to understand/learn all the languages at the same time, the discussion of the neighbor is not considered as noise anymore but useful information that all the couples can jointly help to reach its destination through adequate hops. No shouting is needed anymore and all the couples can discuss simultaneously. In fact, more couples in the room means more opportunities for information to transit.

II-C. A Historical Perspective

In his early papers, Shannon [3], [4] already described the first learning devices and discussed theoretical developments of self-reproducing machines in very simplistic cases. Nowadays, Mobile Flexible Networks face much broader and complex problems due to three facts.

- The systems are heterogeneous in transmit power, frequencies, range, QoS requirements, spectral efficiency and standards.
- There may be limited or no communication between different systems and decisions have to be made based on such distributed information.
- Finally, the systems change rapidly and the flexible network needs to adapt fast and anticipate future evolutions.

One of the most challenging problems in the development of Mobile Flexible Networks is to manage complexity and develop the right tools to reason about the spatial and temporal dynamics of complex systems. In order to break the spectrum efficiency barrier, the research should interdisciplinary and is a blend of:

1) **Statistical inference methods**[5] to build devices which can carry plausible reasoning.
2) **Game theoretic techniques** [6] (based on rational players) to promote distributed resource allocation schemes.
3) **Random matrix and free probability theory** [7], [8] to reduce the dimensionality of the network i.e find the parameters of interest in a network rather than optimizing through simulations with 1 billion parameters.
4) **Control theory** [9] to understand the use of feedback/signalling mechanisms.
5) **Physics** [10] to study how information can be processed, stored, and transferred in the network.
6) **Network Information theory** [11] to understand the fundamental network limits achievable with intelligent devices.
7) **Wireless cryptography** [12] to understand the rate reduction of secure systems in highly mobile environments.

III. THE THEORETICAL FOUNDATIONS OF MOBILE FLEXIBLE NETWORKS

In this section, we discuss the challenges and research opportunities in the field of Mobile Flexible Networks.

III-A. The uncertainty foundations

Mobile Flexible Networks take benefit of the high number of interacting devices to schedule adequately information. However, as the number of devices increases, the number of degrees of freedom to estimate in the network increases as well which incurs a diminishing return on the effective capacity scaling of these networks. In the case of finite energy devices, there is an actual limit on the number of degrees of freedom that one has to take into account (typically, one should only coordinate a subset of the base stations on a subset number of carriers which depends on the time/frequency/space coherence of the network topology). This is reminiscent of previous results already obtained in the analysis of the capacity of non-coherent multiple antenna systems [13] where it is shown that one should use only a subset of the transmitting antennas in MIMO systems related to the coherence time. In the frequency domain, similar results [14] have shown that for finite energy devices, one should only use a subset of the bandwidth, related to the bandwidth coherence. Indeed, as the energy is finite, the transmitter will spread its channel estimation energy across all the degrees of freedom incurring an inadequate estimation of the different degrees at the receiver. Therefore, the receiver reduces considerably its ability to recover the data as the number of degrees increase, compared to the case where only a subset is selected. One main research topic should be to extend the previous results to Mobile Flexible Networks where users/base stations/mobility pattern/bandwidth play all an identical role and provide an expression of the non-coherent capacity of these systems for design purposes.

III-B. The large dimension foundations

In the design and analysis of wireless networks, researchers frequently stumble on the scalability problem, in other words as the number of nodes in the network increases, problems become harder to solve. Some examples are the following:

1) In routing: As the network size increases, routes consists of an increasing number of nodes, and so they are increasingly susceptible to node mobility and channel fading.
2) In transmission scheduling: The determination of the maximum number of non-conflicting transmissions in a graph is a NP-complete problem.
3) In capacity of wireless Networks: As the number of nodes increases, the determination of the precise capacity region becomes an intractable problem.

Nevertheless when the system is sufficiently large, one may hope that a macroscopic view would provide a more useful abstraction of the network. The properties of the new macroscopic model would, however, consider microscopic considerations. Indeed we may sacrifice some details, but this macroscopic view will preserve sufficient information to allow a meaningful network optimization solution and the derivation of insightful results in a wide range of settings.

There has been some recent work showing how physics tools and random matrix theory [15] can capture most of the complexity of random networks in order to obtain some insightful features on the ensemble behavior. Starting from the work by P. Jacquet [16] in that area, a number of research groups have worked on massively dense adhoc networks using tools from geometrical optics [16], percolation theory [17], continuum models [18], [19] as well as electrostatics [20], [21], [22]. The challenges ahead should be to pursue this analogy with more sophisticated models related to physics ([23]).

III-C. The statistical inference foundations

A question that naturally arises in mobile networks is the following: "From a set of K noisy and non necessarily equally sampled measurements, what can a terminal extract in terms of useful information on the network? Moreover, once this information has been extracted, how can the terminal exploit (through dissemination, decision process, etc..) that information?". Recent results on free deconvolution [24] have been quite successfully applied in recent works [25] to extract information (where the information was related solely to the eigenvalues of the random network) for very simple models i.e the case where network is unitarily invariant (meaning that basically, some kind of invariance or symmetry in the problem). Extensions to more sophisticated models need to be addressed in the case of Mobile Flexible Networks as in [26], [27].

III-D. The security foundations

Security is a main issue in Mobile Flexible Networks where perfect secure transmissions become increasingly difficult to obtain in highly mobile environments. In his seminal work [12], Shannon formalized the concepts of capacity (as a transmission efficiency measure) and equivocation (as a measure of secrecy). While the concept of capacity has been extended to fading channels with the introduction of concepts like the outage capacity or the ergodic capacity, similar paths are yet to be developed concerning equivocation. Basically, for secure Mobile Flexible Networks, multiuser secrecy concepts for fading channels [28] should be better formalized to understand the rate reduction due to secrecy.

III-E. The protocol foundations

One of the great issues is to propose a general theory of information theory of Mobile Flexible Networks where the constraints of delay/protocol overhead are taken into account in the notion of capacity. The general network information theory research takes its roots with the work of Gallager in 1973 [11] who offered the pioneering vision for wired networks. In the wireless field, the issue is all the more important that the classical layering approach of communications is not adequate. Although many papers deal with the now famed cross layer design, the issues addressed are still specific and tailored to a given technology which rip off the gains provided by the reusability of the different protocol stacks in the seven layer Open System Interconnection (OSI) framework (with the clear distinction between the physical, the link and higher layers). Hence, what is gained in terms of rates is lost by the lack of its general applicability and therefore requires a full new design of a protocol for each new technology. This is not so appealing for Mobile Flexible Networks, which build on the contrary bridges between systems. We still need to provide cross-layer designs for more general classes of communications schemes (typically for slow to highly mobile networks with a smooth transition between the two).

III-F. The dynamics foundations

In many respect, the design of networks has been made at the equilibria state i.e engineers optimize the parameters when the network has reached its equilibria. The great majority of results focus on the efficiency, the type (Nash if game theoretical tools are used) and performance of the equilibria state. However, very few look at the dynamics to reach the equilibria. This problem becomes all the more important as the number of iterations to reach the equilibria is a critical issue in mobile flexible networks (by the time the network has converged to the equilibria state, the network topology has already changed). The channel state of knowledge window or the stationary time of the environment needs to be at least higher than the time it takes for the algorithms to converge to the equilibria. Due to the very complex nature of the problem, new tools and a thinking of new sort need to be developed taking into account evolution and learning aspects [29], [30], [31].

IV. CONCLUSION

In this paper, we have discussed the challenges facing the design of Mobile Flexible Networks. These networks, if adequately designed, could solve the shortage of spectrum problem by trading spectrum for space. This comes through the use of intelligence and cognition which permits each terminal to acquire knowledge on the topology of the network. This knowledge provides the terminals means to schedule information adequately and benefit from the high number of virtual links (deployed by the high number of interacting devices). The theoretical foundations of these networks are still a matter of research and should be the next challenge in the wireless arena.

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