Cognitive interconnections

Citation for published version (APA):
Liotta, A. (2011). *Cognitive interconnections*. Technische Universiteit Eindhoven.

Document status and date:
Published: 01/01/2011

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 04. Oct. 2023

Inaugural lecture
prof.dr. Antonio Liotta
10 June 2011

/ Department of Electrical Engineering
/ Department of Mathematics & Computer Science

Technische Universiteit
Eindhoven
University of Technology

Cognitive interconnections

Where innovation starts

Inaugural lecture prof.dr. Antonio Liotta

Cognitive interconnections

Presented on 10 June 2011
at the Eindhoven University of Technology

Introduction

Originally conceived as a non-commercial infrastructure, the Internet has gradually morphed into the largest ‘connectivity machine’ ever built. Business, entertainment, social life and politics are heavily reliant on the Web, which in turn requires a fully-operational network. Yet, unlike any other complex machine, the Internet has not been built with the knowledge of what it was later supposed to be doing. So now, many worry that it will fail under the strain of time- and data-intensive applications. HD Video, Cloud Services and the Internet of Things are already making this issue apparent. What will happen when new applications that are not yet in sight emerge? In this lecture I will explain why the time is ripe for a complete overhaul of the net, highlighting its actual flaws. I will discuss the network mechanisms that will help to shape the next-generation Internet, focusing on the prospects and hurdles of ‘cognitive’ networking.

Time for a new Internet

There are substantial reasons to advocate a complete overhaul of the Internet, though only one is undisputable: the Net has ossified. The general-purpose connectivity machine conceived in the 1970s has now become too vast to afford any significant alteration (Figure 1). Today, almost two billion people use the Net. Each terminal practically has a distinct configuration if we consider the variety of terminals available off-the-shelf. This uniqueness is further defined by the range of software running on each terminal, including operating systems, firewalls, antivirus and personal applications. We all enjoy customizing computers and phones, though many end up misconfiguring and destabilizing their own systems. And then, there are several varieties of viruses, Trojan horses, spyware and the lot. All sorts of stable as well as unstable machines are attached to the Net.

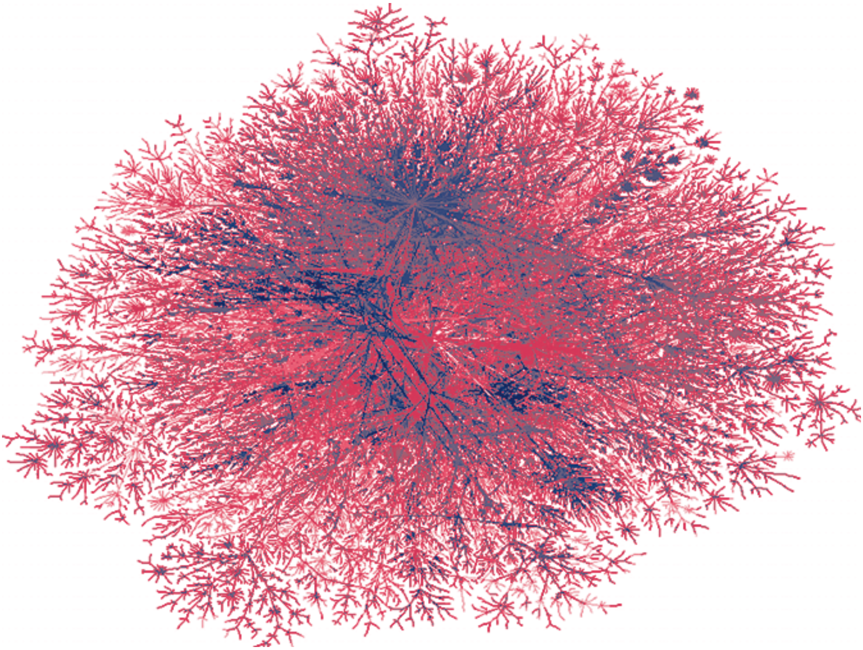

Figure 1

Internet map colored by IP addresses (Courtesy of W.R. Cheswick).

Thus, one would expect the Net to be periodically upgraded to cater for new terminals, usage patterns and threats. Yet, all the attempts made in the last fifteen years to modify fundamental network mechanisms have failed. Important changes have taken place in 1980 (Link State routing), 1982 (Domain Name System), 1983 (Transmission Control Protocol), 1988 (Transmission Control Protocol with flow control), and 1993 (Classless Inter-Domain Routing (CIDR)). 1993 is an iconic year for yet another reason: Mosaic, the very first Internet browser, gives birth to the World Wide Web. However this is also the very last time we would see any significant upgrades into the 'core' network. After CIDR, all other attempts to modify the Net failed. The Net was too big and too complex. Any further innovation started happening at its edge, rather than in the core. The ossification process had started, inexorably [1].

The missing gear box

The Net's stagnation is evident in many sectors. First, despite several attempts to accelerate its engine, the Net still works on a single gear (Figure 2). It moves packets 'just about' fast enough. However, different applications (video, voice, gaming, etc.) operate over different time constraints; thus, new gears are needed. Researchers have put remarkable effort into trying to find practical ways to migrate away from the 'best-effort' nature of the Internet. The Integrated Services (IntServ) framework was the first to design a new gearbox for the Net [2]. IntServ was even standardized in 1994, though following the hype, it became clear that a fine-grained approach operating on each individual data-flow would not work on a large scale. Then the Differentiated Services (DiffServ) architecture was also standardized (in 1998) [2], but after over a decade, it is hardly ubiquitous.

Other attempts to add new gears to the Net were made in the 1990s. Given the prominent trend to distribute audio and video in packetized forms rather than over

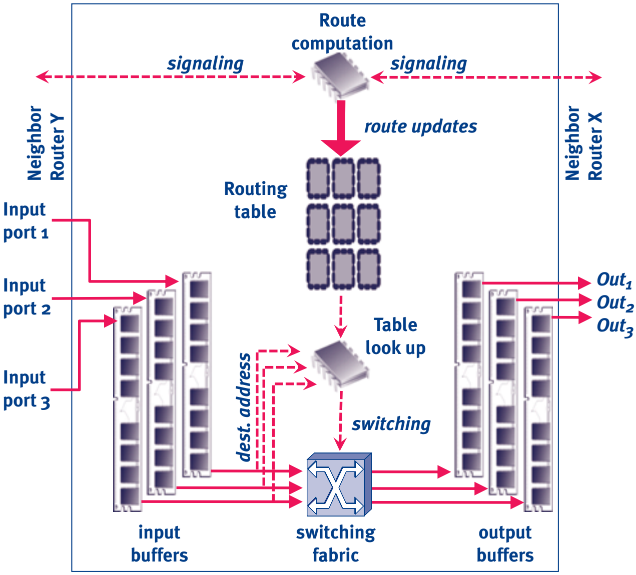

Figure 2

Anatomy of an Internet router [1].

the more conventional radio and television signals, the Net was missing an essential mechanism: ‘broadcasting.’ A large portion of the communications still take place using ‘unicast’ (i.e. point-to-point communication) or ‘multiple unicast’ (as when many clients connect to the same server). This is a fairly rudimentary distribution mechanism, unsuited to applications such as IPTV. When scientists came up with the idea of multicasting in the early 1990s (i.e. to build special distribution trees from server to clients) this seemed like a revolutionary idea. Unfortunately, ‘multicast’ is confined within specific domains, as it was never able to make it to the global Internet.

Which other gears are missing to our beloved Internet? Security, privacy, reliability, efficiency. The list gets longer as we observe the new trends in the ubiquity, mobility and pervasiveness of the emerging applications. Some recent statistics will help in assessing why the time has come to rethink the Internet. Being totally unaware of what the application is doing, the Net is exposed to great risks [3, 4]. In 2009, 81% of emails were spam, accounting for about 73 trillion emails; yet, the Net is disarmed against spam. Denial of service attacks can bring a large corporation to a halt; however, protection against such attacks relies largely on human intervention.

How ubiquitous is the Internet? As of January 2010, an average 26.6% of the global population had Internet access (source: internetworldstats.com). This is a very low achievement, considering also that the Internet penetration statistics provide average values. In geographical terms, the vast majority of the Earth is off the Net (Figure 3). Yet ironically, network access is often needed where there is no infrastructure. A communication network might help coordinate the efforts of a team of engineers whose task is to actually build a network. Communication is

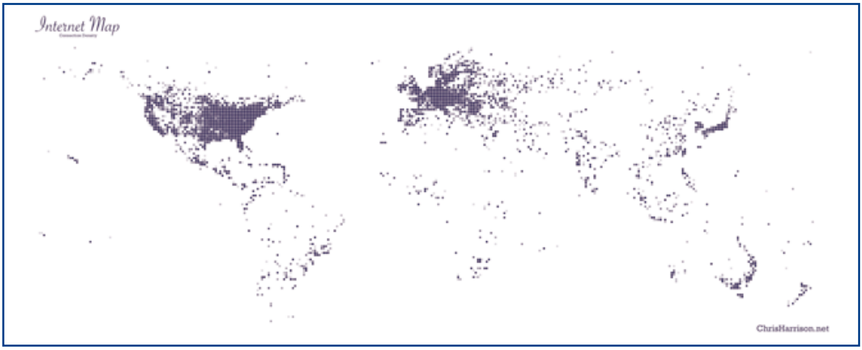

Figure 3

Internet penetration (connection density) in 2007 (Courtesy of Chris Harrison).

also vital for disaster management, i.e. when a catastrophic earthquake takes place. Yet, in this situation, the infrastructure if often affected by power or hardware failures.

How reliable is the Internet? If we actually count the number of packets dropped by the routers, an astonishing rate of 8-10% emerges (internettrafficreport.com). Thanks to a wealth of innovative measures such as 'caching', 'adaptive coding', 'scalable coding' or 'P2P transmission' (to mention just a few) [5, 6, 7, 8, 9, 10] we are still able to run a variety of time-constrained applications [11]. Yet, IPTV or video conferencing can adjust to network degradation only to a limited extent and we already see a hard problem if we wish to transport High-Definition video. The current approach is to protect video streams through a combination of buffering and retransmission. These are rudimentary mechanisms which do not fight congestion at its roots and reduce our ability to support data-intensive (time-constrained) applications (both buffering and retransmissions incur extra latency and congestion). There is also another major problem: the very heart of the network, the all-optical trunks, is not even able to buffer data (optical buffers are still a chimera).

In my book 'Networks for Pervasive Services: six ways to upgrade the Internet' [1] I look at many more shortcomings than it is possible to discuss here. I give evidence as to how the Internet is failing to meet the requirements of the emerging applications and will soon be unable to sustain economic growth at current rates. In essence, the current network mechanisms are unable to support dynamic connections, parallel transmissions and data-aware communications. Our network is not geared for ultra-large scale connectivity and burns much more energy than it should. It is paradoxical that current routers still consume 80% of their power and memory in the process that maps individual packets to suitable output ports (Figure 2) [12]. Even more astounding are the energy consumption figures coming from network operators. A 2007 study by Telecom Italia unveiled network consumption of over 2TWh, representing 1% of the total national demand. This ranks the company as the second largest energy consumer, after the national railways [13].

Considering the crucial role that networks play in our digital society, scientists have developed new energy-efficient routing algorithms based on data flows, information awareness and context dependencies. The next-generation Internet will certainly have to incorporate such advances, but the deployment roadmap is still unclear.

The future Internet of Things

The time when the Internet was for the sole use of computers is over. Our technology roadmap is going towards the *Internet of Things* (IoT) [14, 15], a digital infrastructure where anything having any kind of network interface will be part of the Net. The convergence between the conventional stationary Internet and the cellular network has given tremendous impulse to the digital society [4]. Even greater breakthroughs will come from the interconnection of everyday objects, sensors and actuators.

The realization of the IoT poses ambitious scientific hurdles, though it certainly has enormous potential. With virtually anything on the Net, from the domestic appliances to clothing and biometric sensors, the network will suddenly assume a ‘massive’ scale.

Yet the biggest challenge will probably come from the huge functional diversity among the devices. RFIDs[1] can do very little in terms of networking but provide a cheap way to locate a myriad of objects. Multiple sensors may collaborate to provide environmental monitoring information, but will have substantial computational and energy constraints. Intelligent camera systems may solve complex surveillance problems, though they will incur severe traffic onto the network.

The size and diversity of the IoT cannot be handled by the current IP protocol [16]. On the other hand, the IoT will be able to rely on a wealth of contextual information that will enable greater routing intelligence. The IoT will not only propagate contextual information ‘where’ and ‘when’ it is needed, but it will also make use of the context to better operate the network itself.

Once we make the move to attaching anything to the Net, the network will become the largest control system ever built. The network’s ‘things’ will provide *sensory,*

---

[1] Radio Frequency Identification (RFID) is a technology that uses communication via radio waves to exchange data between a reader and an electronic tag attached to an object for the purpose of identification and tracking.

but also *transducing* and *actuation* capabilities. Actuators, for example, motors, pneumatics and hydraulics, can move objects and pump fluids. Electrical relays can switch on the heating system or turn off the lights.

The transducers will further enhance the network's self-sufficiency. Researchers are making progress in the area of energy-harvesting transducers that can capture small but usable amounts of energy from the environment. This energy can be used to run sensors and network interfaces.

The next-generation network will be able to *grasp* and simultaneously *influence* its environment. Scientists are investigating the paradigm shift required to make the most of these new capabilities.

Small interconnections

There is no doubt that the Net is getting bigger, more complex and increasingly dynamic. At the same time, the perturbations created by emerging applications are more and more intense and erratic. The Net is a complex system that is constantly changing and expanding. The routing protocols must keep everything connected; they must discover short paths across such a massive network.

One way to keep large networks 'small' is to increase the number of links, making the network denser. This is easier said than done. Adding new capacity on the physical network is costly. In fact, the current Net is relatively sparse; it has a number of links roughly of the same order of magnitude as the number of nodes.

Things get more complicated if we try scaling up the network while at the same time ensuring 'stability.' Suppose we can add new links. How do we know which node pairs would benefit the most from the extra capacity? Where do we add capacity in a constantly changing network? How can we make this choice automatically?

Ironically, while the *computer networks* community has created a marvelous yet complex digital ecosystem, fundamental breakthroughs have also been achieved beyond the technologists' circle. Physicists, biologists, mathematicians and sociologists have been studying biological [17] and neural networks [18] that are far more complex than the present Internet [19, 20]. Thus, understanding the properties of the 'natural' networks should be the starting point for those who are rethinking the Internet [21, 22, 23].

Perhaps one of the most remarkable discoveries is the *small-world* phenomenon, which is present in most complex networks [19]. Apparently, the networks resulting from a natural evolution process are able to build short paths, irrespective of the number of nodes. A fascinating yet not fully proved theory is that in natural networks, any node is, on average, six hops away from any other node – this is known as the 'six degrees of separation' property or 'small-worldness' (Figure 4).

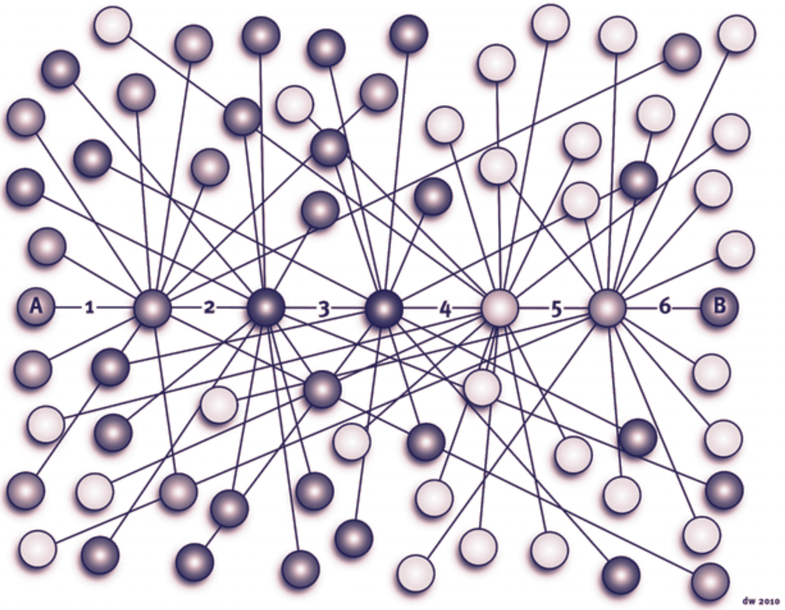

Figure 4

The small-world phenomenon (six-degrees of separation) in 1967 experiment by psychologist Stanley Milgram.

Another outstanding property of natural networks is known as *scale-freeness* [19]. Scale-free networks exhibit the same interconnectivity distribution, no matter how big the network grows (Figure 5). While *small-worldness* is key to scalability, *scale-freeness* is crucial for robustness and stability.

The mechanics of small-world and scale-free networks is not fully understood. However, scientists have already unveiled several mysteries. We have enough knowledge to start designing routing protocols that can make a large network 'small.'[2] We know that a well-designed network must have short paths. This can be achieved if the network has the 'right' mixture of low- and high-degree nodes and of weak and strong links [24].[3]

---

[2] Recent literature describing the properties and mechanisms of small-world and scale-free networks is included in our 'References' section.

[3] A link is 'weak' when its addition or removal does not significantly change the mean value of a target measure (P. Csermely, 'Weak Links', Springer 2009).

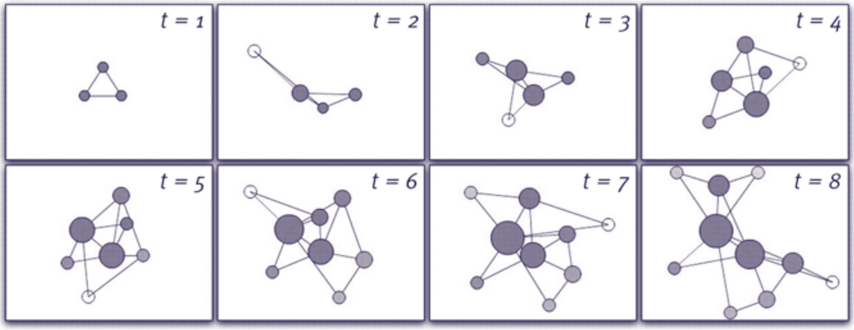

Figure 5

Birth of a scale-free network (A Barabási, R Albert Science 1999;286:509-512. Copyright AAAS).

Scientists have discovered a number of counter-intuitive properties that have significant potential for the redesign of routing protocols. For instance, weak links play a crucial role in reducing the network diameter as they build long-distance bridges between nodes that would otherwise be poorly connected. Because of their nature, weak links tend to be transient. It seems to defy logic, but scientists have discovered that it is precisely this volatility that makes weak links so crucial in kicking the network out of suboptimal configurations. Weak links make it possible to propagate signaling information more rapidly and towards areas that would otherwise not be reached. Weak links hold the secret of *stability*. However, weak links cannot exist without the strong ones. In fact, the natural networks have a continuous spectrum of link strengths.

Extensive studies of complex networks have unveiled how difficult it is to pursue multiple performance goals. Network *speed* and *stability* are often conflicting targets. It is a myth that networks' diameter can be merely reduced by increasing the average node degree. Nodes with a large number of neighbors are called *hubs*. Hubs multiplex traffic, so they are important. However, hubs come with a problematic side effect. They make the network vulnerable. Hubs have huge responsibilities, so if they are attacked, large portions of the network are affected. Hubs not only propagate genuine data, but also speed up the spreading of computer viruses or any other destabilizing agent.

Ironically, hubs and strong links help to improve transmission speed, but do not play a positive role when it comes to stability and robustness. Another counter-intuitive finding is that, in addition to weak links, *bottlenecks* can also help make networks more *robust*. Bottlenecks limit the network throughput, but often generate new weak links. Bottlenecks force networks to redistribute the load and trigger a rewiring process that is crucial in protecting networks against cascading failures. Scientists such as A.E. Motter have proved that a selective removal of network elements makes the network more robust [25].

One of the problems of the current routing protocols is that they strive for a ‘uniform’ network. They pursue routing efficiency but neglect other essential properties. Looking at the most complex natural networks, we see that they are not only transmission-efficient, but also tolerant to incredible amounts of failures, errors, noise and dynamics. Small-world, scale-free networks have a mix of randomness, nestedness[4], disuniformity, volatility and unpredictability. They have a variety of nodes (hubs[5], rich clubs[6], VIP clubs[7], leaves and bottlenecks) and links (bridges, weak and strong links). As part of their evolution, the natural networks have learned how to orchestrate this variety of elements and respond to new forms of perturbations. One of the most stimulating challenges faced by the computer networks scientists is to unlock the mysteries of the natural networks and find ways to mimic their mechanisms. Substantial progress in this direction has been made under the banner of ‘cognitive and autonomic networks.’

---

[4] *Nestedness* indicates the hierarchical structure of networks. Each element of the top network usually consists of an entire network of elements at the lower level. Nestedness helps us to explain the complexity of networks.

[5] *Hubs* are connection-rich network elements.

[6] In hierarchical networks, the inner core becomes a *rich club* if it is formed by the hubs of the network. For example, in the Internet, the routers form rich clubs.

[7] In VIP clubs, the most influential members have low number of connections. However, many of these connections lead to hubs.

Cognition for engineers

The Internet is designed in separate layers, making individual elements unaware of the network status experienced by other elements. Each layer reacts to external stimuli independently from the others. Thus adaptations and responses take place after a problem has occurred and are mostly suboptimal. The complexity and diversity of today's internetworked systems can no longer be embraced by such a simple model. The theoretical framework of *cognitive networks* introduces a new set of capabilities that go far beyond the simple reactive mechanisms of the Internet.

Our understanding of the natural cognitive processes is still not perfect, but we know that 'cognition' implies a system that is both context-aware and self-aware. Actions are based on reasoning, autonomic operations, adaptive functionality and self-manageability.

A simple cognition process was introduced by Boyd in 1986 to help armed forces understand the strategies of their adversaries [26]. He modeled cognition as an OODA loop, standing for Observe, Orient, Decide and Act, as shown in Figure 6.

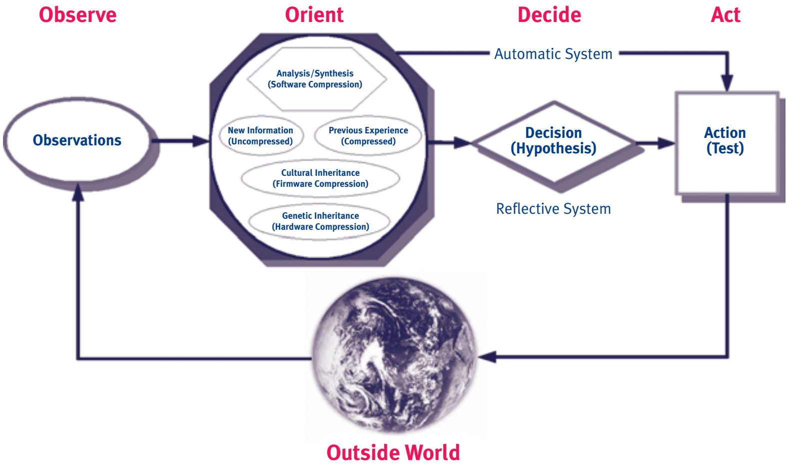

Figure 6

The OODA loop (credits: http://committeeofpublicsafety.wordpress.com/).

This is still a very simple model, which misses three important elements: 1) a direct line between the context (environment) and the orientation; 2) a direct line between context and decisions; and 3) a learning module, which plays a central role in a cognitive system.

A very similar model has been proposed more recently by IBM with the aim to build complex software that mimics the human autonomous nervous system. The IBM MAPE model (standing for Monitor, Analyze, Plan and Execute) has given birth to 'autonomic computing' [27], 'autonomic networks' [28] and 'autonomic management' [29]. MAPE incorporates a knowledge component, which may be realized with learning and reasoning capabilities, opening a brand new avenue towards self-managed systems (Figure 7).

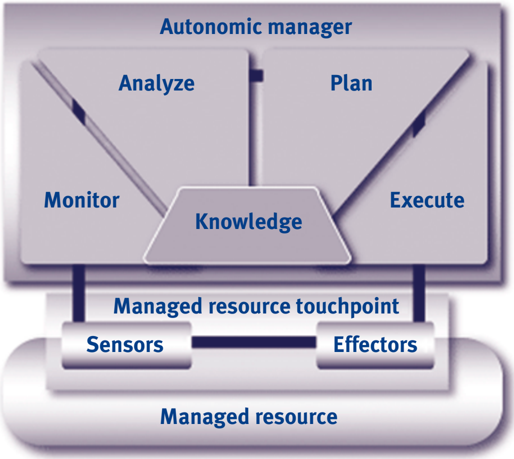

Figure 7

The anatomy of autonomic computing.

A fairly pragmatic cognitive cycle has been introduced by Mitola in the context of cognitive radios [30]. In his view, the cognition process is a state machine including multiple loops among six components: Observe, Orient, Plan, Decide, Act and Learn. As of today, the OOPDAL loop is the most elaborate 'artificial' cognition process and represents the foundations of cognitive networks.

Learning at the heart of the cognition process

When applied to the construction of complex networks and systems, cognition feedback loops such as OODA, MAPE and OOPDAL manage to extrapolate structures and patterns even though these may not be immediately apparent. The very heart of cognition (and its application to performance optimizations) is the ability to learn from past decisions and use this knowledge to influence future behavior.

Do we know how to realize machines that can learn? If we aimed to mimic the elaborate ways in which animals learn, the answer would be discouraging. However, since its conception in the 1960s, the *machine learning* research area has made tremendous progress. Scientists have developed a wealth of algorithms that can ”improve their performance through experience gained over a period of time without complete information about the environment in which they operate” [31].

The application of machine learning to cognitive networks is still in its infancy. However, we have several tools, algorithms and methods at our disposal [32]. *Neural networks* use a bottom-up approach, simulating the biological neurons and pathways that the brain is thought to use. *Pattern recognition* could be used to categorize network events and responses. *Genetic algorithms* imitate the process of evolution (selection, recombination and mutation) to explore large solution spaces for local optima. *Kalman filters* contain adaptive algorithms for feedback control [33]. They estimate the actual and future state of the system based on noisy Gaussian measurements. *Learning automata* are simple methods for teaching a process to an unknown feedback system [34]. They work particularly well if the problem is distributed and requires very little state information, which is, in fact, the case for routing problems.

The application of machine learning to complex networks has enormous potential because of its ability to function even with incomplete information about the system.

Cognitive networking

The OOPDAL cognition cycle [30] models the process occurring at individual nodes, but does not fully capture the complexity of a whole network. Cognitive networks require more than just a collection of cognitive nodes whose cognition process must take into account end-to-end goals to avoid situations in which local optimizations lead to poor overall performance or instability.

For this reason, Doyle and Forde have modified the OOPDAL cycle, including both node-level and network-wide cognition processes [35]. Combining these two processes is not straightforward. It will be even more difficult to develop the required distributed algorithms that will have to realize a cooperative machine learning system. This is perhaps one of the most ambitious hurdles of cognitive networks.

Managing cognition and autonomics

Networks are becoming increasingly complex and heterogeneous. Networks are nested within networks, virtualized, overlaid, sub-netted. Some sections of the Internet are 'managed,' e.g., by network operators or ISPs. However, there is a steep increase in 'unmanaged' networks (e.g., wireless home networks), 'spontaneous' networks (e.g., *ad hoc* networks) and 'content-driven' networks (e.g., P2P networks). Several researchers are investigating how to bring the power of the natural evolutionary networks into the Net [17, 18, 36]. By mimicking biological mechanisms, the 'bio-inspired' computer networks promise efficiency, robustness, scalability, but also adaptivity and evolvability.

In the future, big chunks of the Net will be 'autonomic' [37]. Networks will be able to learn how to respond to new kinds of perturbations. They will be able to absorb and disperse the bad signals whilst transmitting the good ones. They will be resilient to viruses, failure or catastrophic events.

Many networks will be self-managed [15, 29], though human intervention will still be needed. It will be necessary to incorporate higher-level management mechanisms to manage the complex entanglement of autonomic elements. There is a possibility that the introduction of sophisticated automatisms will generate new problems in terms of signaling, stability, security and trust. The multiplicity of autonomic systems will interact, influencing each other. How can we ensure that such interactions do not degenerate or create interferences or instabilities?

Just as in the evolutionary networks within nature, the different subsystems of the future Internet will morph over time. However, computer networks are influenced by multiple factors that we have not yet learnt how to master. The evolution of the Net is affected in different ways by technology, but also by economic, political, legal and social elements. Until we find out how to realize a self-sustained digital ecosystem, we will continue to need human intervention for purposes such as global optimization, regulatory obligations, law enforcement, business and provision of quality levels [38]. Thus, for many years to come, it will still be necessary to monitor cognitive and autonomic processes and possess a means to influence them positively.

Acknowledgements

The idea of working on cognitive networks has been in my mind for several years, but it started as a concrete project only after I moved to Eindhoven University of Technology (TU/e), in the Netherlands. At TU/e I found the necessary resources and, even more importantly, a renewed inspirational energy. I want to thank the colleagues of the Departments of Electrical Engineering and Mathematics & Computer Science for sharing their expertise and ideas. I am very grateful to Prof. Koonen and Prof. Lukkien for their continued support since our very first interaction in 2007.

I would not be here without the generous advice received from my earlier academic mentors, Prof. Barili and Prof. De Lotto (Università di Pavia), Prof. Pavlou and Dr. Knight (University College London), Prof. Simeonidou and Prof. Henning (Essex University).

My research would not have been possible without the dedication and trust of the people who have worked with me. I cannot list all the students and researchers whose hard work has been instrumental in my career. Yet I do wish to mention those who are currently sharing their research ambitions with mine: George Exarchakos, Vlado Menkovski, Archi Delphinanto, Akis Kokkinis, Loizos Kanaris, Ling Lin, Stefano Galzarano, Ma'mon Aldiabat, and Aravind K. Gopalakrishna.

Finally, my utmost gratitude goes to my parents, Pina and Mario, for fostering my passion for research. Without their encouragements and unconditional love I could have not survived the big hurdles of life and I would not have had the strength to emigrate from Sicily in 1986. My sister, Linda, and my brothers Pietro, Francesco and Alessandro, have helped me in different ways and during different phases of my life. They have shaped my personality and enriched my life in many ways. Finally, thank you to my dear wife, Maria: for fourteen years together; for believing in my dreams and giving me access to yours.

Dixi.
Ik heb gezegd.

References

1. **A. Liotta**, G. Exarchakos, Networks for Pervasive Services: Six Ways to Upgrade the Internet. Springer (2011).
2. M. Marchese, QoS Over Heterogeneous Networks. Wiley (2007).
3. **Antonio Liotta**, Alessandro Liotta, Privacy in Pervasive Systems: Legal Framework and Regulatory Challenges. Pervasive Computing and Communications Design and Deployment: Technologies, Trends, and Applications. Idea Group Publishing (2011).
4. **Antonio Liotta**, Alessandro Liotta, P2P in a regulated environment: challenges and opportunities for the operator. BT Technology Journal. 26, 150-157 (2008).
5. M. Alhaisoni, **A. Liotta**, Characterization of signaling and traffic in Joost. Peer-to-Peer Networking and Applications. 2, 75-83 (2009).
6. M. Alhaisoni, **A. Liotta**, M. Ghanbari, Improving P2P Streaming Methods for IPTV. International Journal on Advances in Intelligent Systems. 2, 354-365 (2009).
7. M. Alhaisoni, M. Ghanbari, **A. Liotta**, Scalable P2P Video Streaming. International Journal of Business Data Communications and Networking. 6, 49-65 (2010).
8. M. Alhaisoni, M. Ghanbari, **A. Liotta**, Localized Multistreams for P2P Streaming. International Journal of Digital Multimedia Broadcasting. 2010, 1-13 (2010).
9. M. Alhaisoni, M. Ghanbari, **A. Liotta**, Resource-Awareness and Trade-off Optimization in P2P Video Streaming. International Journal of Advanced Media and Communications, special issue on High-Quality Multimedia Streaming in P2P Environments. 41, 59-77 (2010).
10. M. Alhaisoni, **A. Liotta**, M. Ghanbari, Resilient P2P Streaming. International Journal on Advances in Networks and Services. 3, 209-219 (2010).
11. F. Agboma, **A. Liotta**, Quality of experience management in mobile content delivery systems. Telecommunication Systems. (2010).
12. L. Roberts, A radical new router. Spectrum, IEEE. 46, 34-39 (2009).

13. C. Bianco, F. Cucchietti, and G. Gri, Energy consumption trends in the next generation access network - a telco perspective, International Telecommunications Energy Conference, INTELEC, Sep. 30–Oct. 4, Rome, Italy (2007).
14. H. Chaouchi, H.: The Internet of Things: Connecting Objects. Wiley-ISTE (2010).
15. S. Kim, et al., Towards Management Requirements of Future Internet. Challenges for Next Generation Network Operations and Service Management. pp. 156-166. Springer (2008).
16. I.F. Akyildiz, M.C. Vuran, Wireless Sensor Networks. John Wiley & Sons Inc (2010).
17. M. Farooq, Bee-Inspired Protocol Engineering: From Nature to Networks. Springer (2010).
18. S. Haykin, Neural Networks and Learning Machines. Prentice Hall (2008).
19. Xiao Fan Wang, Guanrong Chen: Complex networks: small-world, scale-free and beyond. IEEE Circuits and Systems Magazine. 3, 6-20 (2003).
20. F. Dressler, O., Akan, Bio-inspired networking: from theory to practice. IEEE Communications Magazine. 48, 176-183 (2010).
21. M. Buchanan, Nexus: Small Worlds and the Groundbreaking Theory of Networks. W. W. Norton & Company (2003).
22. K. Gammon, Four ways to reinvent the Internet, 10.1038/463602a, (2010).
23. D.D. Clark, et al., Making the world (of communications) a different place. SIGCOMM Computer Communications Review. 35, 91-96 (2005).
24. P. Csermely, Weak Links: The Universal Key to the Stability of Networks and Complex Systems. Springer (2009).
25. A.E. Motter, Cascade control and defense in complex networks. Phys. Rev. Lett. 93, 098701.
26. John Boyd, A discourse on winning and losing: patterns of conflict. Report (1986).
27. J. Kephart, D. Chess, The vision of autonomic computing. IEEE Computer (2003).
28. S. Dobson et al., A survey of autonomic communications. ACM Transactions on Autonomous and Adaptive Systems. Vol. 1(2) (2006).
29. B. Jennings et al., Towards autonomic management of communication networks. IEEE Communications Magazine (2007).
30. J. Mitola, G.Q. Maguire, Cognitive radio: making software radio more personal. IEEE Personal Communications. Vol.6(4) (1999).
31. M.A.L. Thathachar, P.S. Sastry, Networks of Learning Automata. Kluwer (2004).

32. R.W. Thomas et al., Cognitive Networks. Chapter in *Cognitive Radio, Software Defined Radio and Adaptive Wireless Systems*. H. Arslan (Ed.). Springer (2007).
33. E. Brookner, Tracking and Kalman Filtering Made Easy. Wiley (1998).
34. S.N. Kumpati et al., Learning Automata: an Introduction. Prentice Hall (1989).
35. L. Doyle, T. Forde, The Wisdom of Crowds: Cognitive Ad Hoc Networks. Chapter in *Cognitive Networks*, Q.H. Mahmoud (Ed.). Wiley (2007).
36. S. Dhillon, Ant Routing, Searching and Topology Estimation Algorithms for Ad Hoc Networks. Delft University Press (2008).
37. D. Papadimitriou, Future Internet: The Cross-ETP Vision Document. (2009).
38. V. Menkovski, G. Exarchakos, **A. Liotta**, A. Sánchez Cuadra, Quality of Experience models for Multimedia Streaming. International Journal of Mobile Computing and Multimedia Communications. (2010).

Curriculum vitae

Prof. Antonio Liotta was appointed full-time professor of Communication Network Protocols in the Departments of Electrical Engineering and Mathematics & Computer Science at Eindhoven University of Technology (TU/e) on October 1, 2008.

Antonio Liotta (1968) holds a 'Laurea' degree in Electrical Engineering (1994) from the University of Pavia, Italy and an MSc in Information Technology (cum laude, 1995) from Politecnico di Milano, Italy. He gained his PhD in Computer Science (2001) from University College London, UK, with a thesis on distributed monitoring systems. He was appointed Lecturer in 2001 while he was with the University of Surrey (2000-2004). At the University of Essex, UK, (2005-2008) he became Senior Lecturer (2005) and Reader (2007). Since 2008, Antonio has held the Chair of Communication Network Protocols at TU/e where he is creating a multifaceted team in Autonomic Networks.
Antonio is a Fellow of the U.K. Higher Education Academy and an associate editor of the *Journal of Network and System Management* (Springer). He serves the editorial boards of four more journals: the *International Journal of Network Management* (Wiley); the *Computer Science & Engineering International Journal* (AIRCC); the *International Journal of Digital Media Broadcasting* (Hindawi); and the *International Journal of Information Science and Computer Applications*.
During the last decade, Antonio has investigated topical issues in the areas of network and service management and is currently studying cognitive systems in the context of optical, wireless and sensor networks. He has three patents and over 130 publications to his credit and recently authored the book 'Networks for Pervasive Services: six ways to upgrade the Internet' (Springer, 2011 http://bit.ly/pervasive-networks).

Colophon

Production
Communicatie Expertise
Centrum TU/e

Cover photography
Rob Stork, Eindhoven

Design
Grefo Prepress,
Sint-Oedenrode

Print
Drukkerij Snep, Eindhoven

ISBN 978-90-386-2518-8
NUR 986

Digital version:
www.tue.nl/bib/

Visiting address
Den Dolech 2
5612 AZ Eindhoven
The Netherlands

Postal address
P.O.Box 513
5600 MB Eindhoven
The Netherlands

Tel. +31 40 247 91 11
www.tue.nl

Technische Universiteit
Eindhoven
University of Technology