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MESSAGE FROM MMTC CHAIR

Dear MMTC fellow members,

Thank you very much for your strong support to MMTC as always. Here we would like to update you on some latest progresses of TC development on various frontiers, mainly on our IG initiatives and member services.

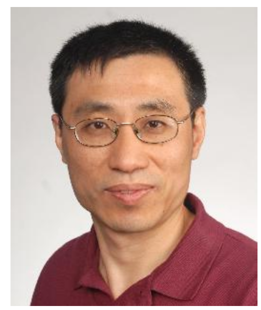
Our TC has built 12 Interest Groups (IGs) to cover the major scope of multimedia communications. The IG teams will represent MMTC in the related IEEE journals and conferences in the capacities of Editorial Board members, Editors, and TPC leaders and members. The preliminary information of the IGs has been introduced in the July issue of the E-letter. To reflect the new IG initiatives, we have updated the MMTC website at http://committees.comsoc.org/mmc/activities.asp, where you can find the IG leader information and IG scopes. Soon you will also find the various journal special issues and workshops proposed by various IGs on the same website. Dr. Honggang Wang (hwang1@umassd.edu) is leading the effort in keeping the website updated. We strongly suggest all our members to join an IG and contribute to these high profile activities, so that your expertise will be utilized effectively for the community.

We plan to set up our online community platform through IEEE ComSoc web site, http://community.comsoc.org, after evaluating several approaches. The platform will incorporate groups and forums for various IGs.

We hope that this community platform will provide a communication and discussion channel among our members. Members are welcome to check the web site now and help us testing it. Dr. Liang Zhou is leading the effort in testing the platform. If you have any suggestion, please email to Dr. Zhou at liang.zhou1981@gmail.com. Please stay tuned as our IG leaders will set up dedicated areas there.

At last but not the least, we would like to encourage our members to submit papers to ICC 2011 at Kyoto, Japan. Please submit your papers to CSSMA (Communications Software, Services and Multimeida Application) symposium, which is the sole symposium sponsored by MMTC. The paper submission deadline is September 20, 2010.

Let us work together to promote our community. Thank you very much!



Jianwei Huang and Bin Wei
Vice Chair, Multimedia Communication TC of IEEE ComSoc.

HIGHLIGHT NEWS & INFORMATION

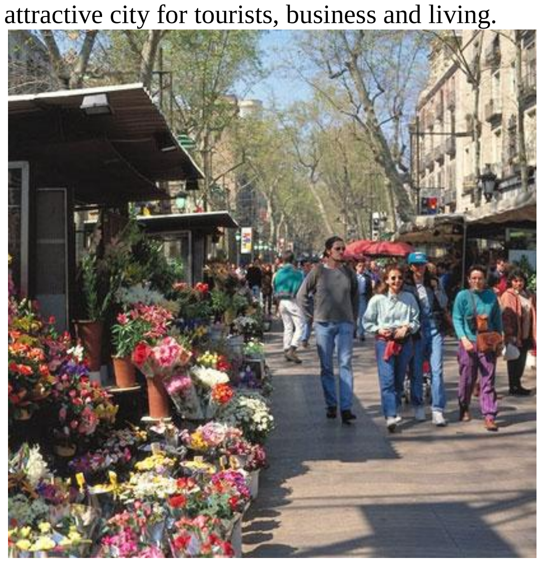
IEEE International Conference in Multimedia and Expo (ICME)

http://www.icme2011.org

IEEE ICME 2011 will be hosted in Barcelona, Spain during July 11 – 15, 2011. Barcelona is a compact city, with history dates back over 2,000 years retaining major relics of its past. Barcelona has a rich cultural life all the year round: opera, ballet, concerts, theatre, festivals, exhibitions, museums, etc. These characteristics make it a unique city with a great diversity of cultural, recreational and commercial facilities. Barcelona has the dynamic and open personality so typical of Mediterranean cities. It is the only major European metropolis with five kilometers of city beachfront. Barcelona enjoys sunshine during all the seasons of the year. You can eat at open-air restaurants or enjoy a drink at any of its many pavement cafes, always on the shores of the Mediterranean.

THE HOST CITY: BARCELONA, SPAIN

Barcelona was founded over two thousand years ago, on the Mediterranean coast, between two rivers. It is located in the north east of the Iberian Peninsula, just a short distance from France. Since its beginnings, the city has been the traditional gateway to Spain. Romans, Arabs and Christians passed through it, as did the diverse cultures which came to enrich its heritage. The traces of this history and diversity can be found as you walk through the city; through its Gothic Quarter built on the Roman ruins; through its art-nouveau Eixample district, which is dominated by Gaudí's exuberant architecture, yet at the same time reveals an ordered and rational urban layout. Diversity and harmony also flourish in the character of the Barcelona people, who are enterprising and hard-working, have a hedonistic streak, and are, in particular, civic-minded and lovers of culture. These traits have made Barcelona into a first-class tourist destination and the perfect setting for meetings and congresses. This open, welcoming city shed its skin and opened up to the sea in order to host the 1992 Olympic Games and is now a modern and attractive city for tourists, business and living.



Transportation

Barcelona has excellent air links, particularly with the majority of Spanish and European cities. Its international airport, located 15 minutes from the city centre, has recently expanded with a new terminal. In 2009, it handled 27,421,682 passengers and 278,981 flight operations, and in 2010 has been awarded as the best airport in Europe. Barcelona is well connected to North America with direct flights from NY, California, Toronto and Montreal. There are also many flights every day from Asia to Barcelona.

The land transport is basically designed on a network of motorways and railway, which radiates towards the most important economic areas of the rest of Spain and connects with the French transport system to the rest of Europe.

Convenient city transportation includes metro, bus, taxi and train. There is a subway system connected from Airport to all interesting parts of the city.

Weather

Barcelona's location on the shores of the Mediterranean means it enjoys a warm climate, with pleasant temperatures all the year round.

	˚C	˚F
Jun	21	70
Jul	25	77
Aug	25	77

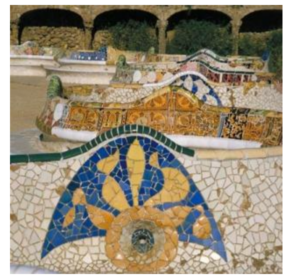
Congress and Conference

Barcelona is one of the cities in Europe and the world which host the greatest number of international congresses. The biggest AI conference (held once every two years) IJCAI will be held the week following ICME 2011. Also, ICCV 2011 the biggest computer vision conference will be held later on in Barcelona. Barcelona gets second position in the ICCA ranking (International Congress & Convention Association, with 135 congresses in 2009, and fifth position in the UIA (Union of International Associations) ranking for the year 2008. Leading multinationals choose Barcelona for their conventions and product presentations. Furthermore, in recent years, Barcelona has proved itself to be one of Europe's most attractive and dynamic cities, and this has made it one of the preferred incentive trip destinations.

Tourism

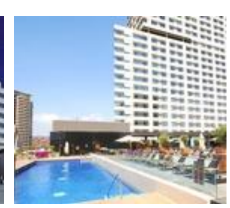
Barcelona has a moderate weather in summer; on the sea, yet close to the mountains; has the perfect mix of museums and shopping; has thousands of affordable gourmet food from all ethnic origins; has nightlife that never stops for the young at heart; architectural masterpieces that many consider the best in the world; and is easily accessible to many other resort towns and cities nearby for people who may desire an extended holiday:

- Museums tours: Gaudi, Miro, Picasso, Contemporary Art, MNAC, Guggenheim (in Bilbao, north of Spain, 4 hours from Barcelona).
- Family tours: Zoo, Aquarium, Port Aventura (in Salou, 40 minutes from Barcelona).
- City tours: Gothic Area, Old Town area, Gaudi Tours…
- Tours to Montserrat (an exceptional Mountain 50 minutes from Barcelona) or Sitges (beautiful small sea village).

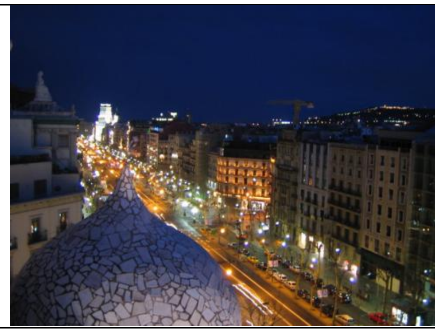
There are many affordable hotels in Barcelona, in addition to those located close to the Tourist Street of La Rambla. Many of these hotels are near a very long beach area where there is miles of beautiful walkway along the beach (Mar Bella etc.) and many in the Sagrida Familia (Magnificent Gaudi Church), Cathedral, Museum areas. If booked early rates around only $100/night is possible. Restaurants with varieties of food, Zoo, Aquarium, Port, cruises, cable car, museums, Historic Architectures are all within walking distance in the Cathedral area.

A big part of the travelling expense is food. Barcelona has one of the best and most varied cuisines in the world. The cost of food often depends on the location of restaurants. ICME 2011 will provide a guide of affordable restaurants in various areas, where people can have excellent varieties of 3 meals a day for $40/day or so.







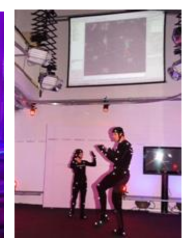

EMBRACE RESEARCH IN A WELCOMING CITY

ICME has been the flagship multimedia conference sponsored by four IEEE societies since 2000. It serves as a forum to promote the exchange of the latest advances in multimedia technologies, systems, and applications from both the research and development perspectives of the circuits and systems, communications, computer, and signal processing communities. An Exposition of multimedia products, animations and industries will be held in conjunction with the conference.

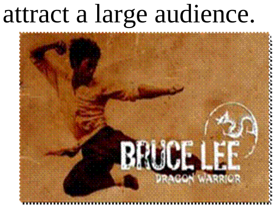
ICME 2011 showcases high quality oral and poster presentations and demo sessions. Best paper, poster and demo awards will be selected and recognized in the conference. Extended versions of oral papers will be considered for potential publication in a special section of IEEE Transaction on Multimedia. ICME 2011 features IEEE societies sponsored workshops, as well as call for workshop proposals. We encourage researchers, developers and practitioners to organize workshops on various new emerging topics. Industrial exhibitions are held in conjunction with the main conference. Job fairs, keynote/plenary talks and panel discussions are other conference highlights. Proposals for Tutorials and Workshops are invited.

Conference Events

A highlight will be a tour to the state-of-the-art Medialab at LaSalle-URL, which is a unique environment of image and 3D motion capture in a single place. It combines a TV set with the classical lighting and chroma keying facilities with a 24 VICON motion capture cameras. It was opened in 2008 and is the largest of its kind in Europe.



An Exhibition area will be maintained for Industrial Displays and Expo. Industrial participants such as Digital Legends Entertainment, who specializes in the handheld and mobile market, e.g. iPad, will certainly attract a large audience.



Regular paper submission deadline:

November 29, 2010

More details are available at:
http://www.icme2011.org

We also invite corporate sponsors, whose contribution will be acknowledged according to the level of sponsorship.

"*Be our guests*"

--- ICME 2011 Organizing Committee ---

SPECIAL ISSUE ON MULTIMEDIA IN FEMTOCELLS

Multimedia In Femtocells

Guest Editor: Mischa Dohler, CTTC, Spain
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Driven by the relentless trend of diminishing cell sizes and exploding demand for wireless data-hungry services, and possibly also by the increasing electricity bills for operators, the birth and growth of femtocells is not a surprise. Said femtocells, also sometimes referred to as small cells, are typically installed at customer premises by the customer. Advantages for network operators are obvious: higher data rates in indoor areas typically shadowed from overlaying macro/micro cellular networks, offload of high-rate traffic from macrocells to femtocells, improved services and thus additional billing opportunities, and the electricity bill eventually being paid by the customer. It is hence no surprise that the femtocell revolution was mainly driven by industrial circles for many years, with academia only recently having joined the excitement in this emerging area with some 200 scientific papers published until today.

And a revolution it is! Indeed, the deployment of femtocells, i.e. the exact choice of placement in the home/enterprise/etc, is – for the first time – not been under the control of the network operator. This has some serious implications, notably on the interference each of these femtocells generates to and perceives from surrounding macro/microcells as well as adjacent femtocells. Given these and other constraints, so the industrial and academic community was investigating in past years, does capacity and performance really improve? And, in the context of this special issue, is any potential improvement in performance sufficient to support demanding multimedia applications? Furthermore, is the seemingly performance-driven upsurge in femtocells being overshadowed by a so-far-not-thought-of and unprecedented femtozone service “culture”?

A special issue solely dedicated to this topic has hence been overdue. I have thus aimed at collecting some position and vision papers from leading personalities in industry and academia in the field, who stem from different communities and have some very differing backgrounds, and who deal or have been dealing with the topic at hand. This, so I hope, shall serve as a guiding hand for the multimedia and signal processing communities over the upcoming years. I also hope that this not only serves the academic community but also an industrial community so that multimedia systems and applications in femtocells will become ubiquitous this time 5 years from now.

I have assembled these six papers in the following order. First, “Are We Ready for the Femtolution?” by Willem Mulder and Thomas Wirth, questions whether technology is sufficiently ripe for handling multimedia-type applications. Second, agreeing that time is ripe, “Beyond Coverage: Femto Cells at the Center of the Digitally Connected Home” by Fabio Chiussi, discusses some unique characteristics that set femtocells apart from any other device in the home, describe a few representative examples of the new services, and project what needs to happen in the femtocell industry to make this potentially game-changing opportunity for femtocells a reality. Third, “Femtocell Networks: Perspectives before wide Deployments” by Guillaume de la Roche and Jie Zhang, discusses some major technological challenges prior to femtocell deployments. Fourth, “Green, Cost-effective, Flexible, Small Cell Networks” by Jakob Hoydis and Mérouane Debbah, dwells on the challenges for a cost and environmental-friendly deployment of multimedia femtocells. Fifth, “Next Generation Femtocells: An Enabler for High Efficiency Multimedia Transmission” by Atta ul Quddus, Tao Guo, Mehrdad Shariat, Bernard Hunt, Ali Imran, Youngwook Koa and Rahim Tafazolli, discuss their vision and resulting opportunities and challenges for high-capacity multimedia femtocells. Finally, “The Future of Small Cell Networks” by Holger Claussen and Louis Gwyn Samuel, discusses the near and far future of femtocells.

I hope you will enjoy reading these contributions of this special issue dedicated to multimedia in femtocells.

Mischa Dohler
CTTC, Barcelona
September 2010

Mischa Dohler [www.cttc.es/home/mdohler] is now leading the Intelligent Energy [IQe] group at CTTC in Barcelona, with focus on Smart Grids and Green Radios. He is working on wireless sensor, machine-to-machine, femto, cooperative, cognitive and docitive networks. Prior to this, from June 2005 to February 2008, he has been Senior Research Expert in the R&D division of France Telecom, France. From September 2003 to June 2005, he has been lecturer at King's College London, UK. At that time, he has also been London Technology Network Business Fellow receiving appropriate Anglo-Saxon business training, as well as Student Representative of the IEEE UKRI Section and member of the Student Activity Committee of IEEE Region 8 (Europe, Africa, Middle-East and Russia).

He obtained his PhD in Telecommunications from King's College London, UK, in 2003, his Diploma in Electrical Engineering from Dresden University of Technology, Germany, in 2000, and his MSc degree in Telecommunications from King's College London, UK, in 1999. Prior to Telecommunications, he studied Physics in Moscow. He has won various competitions in Mathematics and Physics, and participated in the 3rd round of the International Physics Olympics for Germany.

In the framework of the Mobile VCE, he has pioneered research on distributed cooperative space-time encoded communication systems, dating back to December 1999. He has published more than 130 technical journal and conference papers at a citation h-index of 22 and citation g-index of 45, holds several patents, authored, co-edited and contributed to several books, has given numerous international short-courses, and participated in standardization activities. He has been TPC member and co-chair of various conferences, such as technical chair of IEEE PIMRC 2008 held in Cannes, France. He is and has been editor for numerous IEEE and non-IEEE journals and is Senior Member of the IEEE. He is fluent in 6 languages.

Are We Ready for the Femtolution?

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1. Introduction

Three years after the introduction of the first Femtocell by Sprint - not afraid of disruptive technologies and business models - in 2007, Femtocells have reached global acceptance in the telecom community, with leading operators launching commercial deployments in Europe, USA, Japan and China [1]. Standards bodies like 3GPP [2] have adopted the Home eNB as an essential part of future standards. The pioneering work in Femto Forum [3], addressing critical issues like interference management [4], plug & play self-configuration, network synchronization, and regulatory issues related to licensed spectrum, has removed the main obstacles for large scale Femtocell rollout. However, this is not where the Femtocell story ends. Actually, we believe this is where the story begins.

Fig. 1. Launch of the world's first Femtocell in 2007

2. Messengers of Fundamental Change

Skype, Google and Apple have become the messengers of fundamental change in the rules of the game. To understand the strategic value of Femtocells for the telecom industry, we have to go back to the radical changes in the value chain, business models and revenue streams in fixed network business. From the invention of the telephone by Alexander Graham Bell in 1877 until recent years, the telecom industry has offered one service, voice, with a simple pay-per-minute business model. Internet, voice telephony, and audio / video broadcasting peacefully coexisted. Incompatible standards for one-way analog audio / video broadcasting, circuit-switched voice telephony and packet switched data networks prohibited competition.

The introduction of DOCSIS-based cable modems with QoS support in 1997 and commercial launch of VoIP by Skype in 2003 enabled competition between cable operators and phone line operators. Although many DSL operators are still blocking third party SIP / VoIP traffic over their network, the Skype algorithms managed to bypass these obstacles, with Skype starting free voice communication to any place having Internet access, even for long distance- and international calls.

Fixed network operators were forced to accept a new role of bit pipe supplier, with flat-fee subscription models and lower margins. Cable operators, who relied for many years on a video broadcasting model spending over 1 GHz Bandwidth for broadcasting of 60 predefined video/audio channels are now also confronted with changes. With the introduction of MPEG4 / H.264 source coding, DSL operators have started interactive video-on-demand services, challenging the traditional video broadcasting model. Personalized audio / video services are replacing the traditional Radio / TV broadcasting business models, and will free up over 1 Gbps potential cable transmission capacity to the homes. Clearly visible in their annual reports, revenue streams have moved to the companies pioneering new services, like Google, Apple, Skype, Ebay and Amazon.

3. Access Anytime, Anywhere: A Plan Coming Together

At the 2010 CTIA wireless convention, Ericsson announced mobile data surpassing voice on a global scale in December 2009. Mobile users have adopted a new lifestyle with Internet, twitter, Google maps, personal information management (PIM) services, and audio / video on demand at their fingertips: Anytime, anywhere!

All enablers supporting this new lifestyle are coming together now:

- LTE rollout by all major operators in 2010 – 2012, offering native IP support, throughput exceeding 100 Mbps, always-on connectivity, and QoS management [5].
- Open interfaces, like the FemtoForum radio resource management/scheduler/sniffer APIs, the GSMA oneAPI for services, and the GSMA VoLTE VoIP API [6].
- The digital dividend enables availability of 700 MHz (USA) and 800 MHz (Europe) spectrum with excellent coverage properties.
- Traditional audio / video / ebook content providers accepting online on-demand distribution models as pioneered by Apple, with limited DRM restrictions.

4. Challenges and Opportunities

Even with the major enablers mentioned above in place, there are still serious challenges ahead. Regarding the spectrum efficiency, the move from 13 kbps voice traffic to multimedia traffic means a traffic increase of a factor of 100 – 1000, which is given the limited available spectrum a serious challenge. Natural evolution only is not enough and new spectrum-efficient concepts are required.

The move to a mix of applications with a quite different set of QoS requirements will require new QoS management concepts. Not only at the air interface, but end-to-end QoS.

One of the most efficient methods to increase network capacity is the reduction of cell-size. Network capacity [bps/Hz/km^2] and the number of cells required scales with the square of the cell-size. The move to significant smaller cell-size, will scale up the network deployment and configuration cost. Introduction of new self-organizing networks (SON) concepts is a mandatory condition to keep network cost-of-ownership (OPEX and CAPEX) acceptable. With the number of cells scaling with the square of the cell-size, also cell-site capital expenditure (CAPEX) makes or breaks the operator's business case.

Finally, smaller cell-size will result in increased interference at the cell-edge. The OFDMA-based air interface in LTE offers new degrees of freedom for interference management by intelligent scheduling and radio resource management (RRM), a potential which is not yet fully exploited.

5. The Role of Femtocells

The main business driver behind rollout of the first Femtocells was customer satisfaction: improved indoor coverage for countryside customers with limited Macrocell coverage at home, and attractive all-you-can-eat subscriptions for calls originating from the home. Femtocells were deployed without adding cost, e.g. macro network traffic, for the operator. However, there is more to gain with Femtocells:

- A strategic presence in the home, with a platform ideally positioned to launch new services.
- Offloading the macro network, by routing multimedia traffic from the home directly to the Internet.
- Increased spectrum efficiency with a cell-size between 10 – 50 m, and re-use of Macrocell spectrum.
- Radiolink quality: the excellent indoor link budget and rich scattered propagation environment enables optimum use of MIMO spatial multiplexing and higher order modulation, e.g. 64-QAM.

6. State-of-The-Art

Demand for higher spectrum efficiency has been driving research for many years. Given the specific properties of the CDMA-based 3G technology, the focus in 3G research has been on PHY layer interference suppression techniques and smart power control, minimizing the noise-raise at the receiver input.

The OFDMA-based LTE air interface has introduced new degrees of freedom for allocation of radio resources, taking into account not only the channel quality (CQI) per user, per subcarrier, but also the user location, interference matrix and QoS requirements.

The proposal for ITU-Advanced presented by the 3GPP TSG-RAN chairman at the ITU workshop on IMT-Advanced October 2009 is an excellent status report on today's state-of-the-art [7]. For LTE Rel. 8 a downlink spectral efficiency for 4-layer spatial multiplexing of 15 b/s/Hz is reported, equal to a peak data rate of 300 Mbps. Latency on the control plane, the time required to set-up a call, is below 50 ms, and the latency on the user plane is below 5 ms.

Advanced CQI, QoS and interference aware RRM / scheduling techniques for LTE-Advanced are currently investigated in the EU-funded BeFemto research project [8]. New spatial techniques for the LTE-Advanced PHY layer, e.g. CoMP, MU-MIMO, downlink beamforming, 8x8 MIMO, and new successive-interference cancellation (SIC) receiver concepts have been investigated in the EU-funded projects WINNER I, WINNER II and WINNER+ [9].

The EU-funded SOCRATES project [10] has developed new concepts for self-organizing networks (SON).

Fraunhofer HHI's Berlin LTE-A Testbed [11] has played an important role in the real-time verification of many of these new LTE-A concepts.

7. Future Research in Multimedia Femto

Topics for future wireless research in Femtocells offering still a rich field of potential innovation include solutions to increase the spectrum efficiency, fulfilling the user's end-to-end QoS demands, and minimizing costs and power consumption.

Spectrum Efficiency

Since frequency spectrum costs are high and spectrum is limited, the spectrum efficiency can be increased by higher reuse of the existing frequencies through cell-size reduction [12], from Macro- to Femtocells with a macro overlay network. The topics to be addressed in future research are all connected to interference-limited transmission with full frequency reuse. These include CQI, QoS- and interference-aware scheduling and RRM with user-grouping, coordinated RRM, exploiting the spatial degrees of freedoms from multi-antenna systems and FDMA through beamforming techniques, active interference management [13] and CoMP transmission, as well as carrier aggregation for multi-band transmission. These topics have to be evaluated in the context of multi-user transmission in system-level environments.

End-to-End QoS and SON

A second important study item is the delivery of end-to-end QoS to LTE phones and data cards in a heterogeneous environment. The challenge is to find optimization algorithms minimizing latency, response time, guarantee a minimum throughput and provide a secure data channel. This is especially important if different backhauling solutions are used, e.g. DSL or cable, potentially crossing public internet nodes, owned and operated by 3rd parties. In this case, a joint optimization of the air-interface and backhaul traffic requires development of new concepts.

The basic pieces of the puzzle for end-to-end QoS management seem to be in place with LTE, the evolved packet core (EPC) and IP multimedia subsystem (IMS) as service layer on top. As with SON, where the basic concepts have been developed, selection of the correct parameter set, and development of the optimization algorithms for a fully integrated system shall be part of ongoing research.

Cost and Power Consumption

Femtocells will be deployed in massive quantities, setting challenging targets for pricing and power consumption. Benchmarks for pricing and power consumption are today's WiFi access point (AP) pricing, and 7 Watt / user average macro network power consumption. The Femtocell concept was developed with handset-technology-reuse in mind. Concept studies and prototypes in e.g. NXP have shown full TS25.104 [14] compliant HSPA Femtocell system in package (SiP) modules based on handset silicon.

For LTE, with SC-FDMA in the uplink and OFDMA in the downlink, any handset technology based Femtocell silicon will definitely need the flexibility of software defined radio (SDR) for reversed uplink / downlink (RX / TX) processing, thus adding SDR to the list of promising research areas. With 1.13 billion handsets sold in 2009, this will create the required economy-of-scale.

8. Conclusion

Are we ready for the Femtolution? First commercial HSPA Femtocell products have shown that the Femtocells are ready for large scale rollout. The major HSPA issues have been resolved, and concepts have been validated. The adoption of LTE by all major operators has created a rich field of new opportunities and study items to be addressed in future research. The main business drivers, boundary conditions, and main challenges are identified. We believe that the telecom industry is ready to serve the new customer demands,

ANYTIME, ANYWHERE!

Acknowledgement

The authors would like to thank Thomas Kaiser, Dimitry Marandin, Hangwang Wu and Manuel Palmowski at mimoOn GmbH, for the encouraging culture and excellent discussions on 3GPP roadmaps and Femtocell interference management, as well as Lars Thiele, Dennis Wieruch, Kai Börner and Thomas Haustein at Fraunhofer Heinrich Hertz Institute, for excellent discussions on current research topics for LTE-Advanced.

References

[1] GSA – Global mobile Suppliers Association, "GSM / 3G Market / Technology Update", June 2010, [Online]. Available at http://www.gsacom.com/downloads/pdf/lte_3gpp.php4
[2] 3GPP, [Online]. Available at http://www.3gpp.org/LTE
[3] FemtoForum, [Online]. Available at http://www.femtoforum.org
[4] FemtoForum, "Interference Management in OFDMA Femtocells", [Online], Available at http://www.femtoforum.org, March 2010
[5] GSMA VoLTE (Voice over LTE), [Online]. Available at http://www.gsmworld.com/our-work/mobile_broadband/VoLTE.htm
[6] GSMA oneAPI, [Online]. Avail. at http://www.gsmworld.com/oneapi/
[7] T. Nakamura, "Proposal for Candidate Radio Interface Technologies for IMT-Advanced Based on LTE Release 10 and Beyond (LTE-Advanced)", October 2009, [Online], Available at http://www.3gpp.org/IMG/pdf/2009_10_3gpp_IMT.pdf
[8] BeFEMTO: Broadband Evolved FEMTO Networks, [Online], Available at http://www.ict-befemto.eu
[9] WINNER: Wireless-World-Initiative-New-Radio, [Online], Available at http://www.ist-winner.org
[10] SOCRATES: Self-Optimization and Self-Configuration in Wireless Networks, [Online], Available at http://www.fp7-socrates.org
[11] T. Wirth, V. Jungnickel, T. Haustein, E. Schulz et. al., "Realtime multi-user multi-antenna downlink measurements," Proc. IEEE Wireless Communications and Networking Conference (WCNC), Mar. 2008.
[12] M.-S. Alouini and A. J. Goldsmith, "Area spectral efficiency of cellular mobile radio systems," *IEEE Transactions on Vehicular Technology*, vol. 48, no. 4, pp. 1047–1066, 1999
[13] 3GPP TR36.921, "FDD Home eNode B (HeNB) Radio Frequency (RF) requirements analysis (Release 9)", March 2010.
[14] 3GPP TS25.104, "Base Station (BS) radio transmission and reception (FDD)", June 2005.

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Beyond Coverage: Femtocells at the Center of the Digitally Connected Home

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Abstract
Femtocells are currently thought primarily as solutions for improved indoor coverage for consumers and capacity offload for operators. However, femtocells can potentially play a much broader role in the digitally connected home by enabling a new class of multimedia and family communications services, referred to as *femtozone services*. In this paper, we discuss the unique characteristics that set femtocells apart from any other device in the home, describe a few representative examples of the new services, and project what needs to happen in the femtocell industry to make this potentially game-changing opportunity for femtocells a reality.

1. Introduction
The femtocell business case is currently been supported primarily by arguments of improved indoor coverage for consumers and substantial cost savings for operators due to capacity offload. Operators plan to use femtocells to deliver high-quality mobile voice and broadband data in the home at price points that make them attractive solutions for landline replacement.

Although these are powerful arguments to drive femtocell deployments, when it comes to sizing the reach of the technology, there are skeptics. Some contend, in fact, that the need for improved indoor coverage appeals to only a fraction of consumers, especially in countries where macro cellular coverage is already excellent, so that consumers' willingness to pay for the devices may be limited; similarly, operators' cost savings alone may not be enough to justify subsidies of femtocells to all consumers, and operators may direct the use of femtocells to "heavy users" only, or to combat churn. Ultimately, the question is: are femtocells destined to be just useful "pain relievers," and settle as a "niche technology" of sort, or are they game-changing devices with universal appeal to drive mass-market adoption and transform the communications experience?

The answer to this question may come from an additional dimension of femtocells that has emerged more recently and is rapidly generating great interest from operators: because of certain unique characteristics, femtocells may enable a new class of services, referred to as *femtozone services*. These new value-added services may have great consumer appeal because they have the potential to transform the way people stay connected with the two things that matter most: their family and their media. Similar services in an enterprise setting may significantly facilitate communications within the workforce and improve workgroup productivity. In this perspective, femtocells are not anymore just "little base stations with a broadband uplink," but have the potential of becoming must-have *consumer home appliances*. For operators, femtocells therefore open a potentially lucrative opportunity to deliver new services and generate a significant lift in ARPU's by using a managed device that is a beachhead into the digital living room.

Because of its unique placement at the convergence point of three networks – cellular network, Internet, and home network – the femtocell can become the ultimate facilitator for converged services. In fact, the femtocell is the *only* home device that knows about *both* mobile *and* home wired networks. Indeed, the femtocell knows about the handsets that camp onto it; the femtocell is also part of the home network, and as such can discover the other home devices connected to it, and act as a seamless bridge between the mobile and the other devices in the home. In addition, the femtocell provides a strong notion of *presence*, i.e., it always knows whether a specific handset (or, by association, the specific family member using that handset) is at home or not, and can use that knowledge to enable interesting new multimedia services or to create new ways to communicate within the family.

In the next sections, we discuss the three unique characteristics of the femtocell that set it apart from any other device in the home (i.e., the PC, the set-top box, the router/home gateway, the media gateway, etc.) as a service delivery platform:

i) Presence;
ii) Seamless Connectivity; and
iii) Managed Services.

We then describe a few representative examples of the new femtozone services and explain what needs to happen within the femtocell industry and the related standard bodies in order to make this potentially game changing opportunity for femtocells a reality.

2. Unique Traits – A: Presence

A femtocell defines a corresponding area around it, referred to as the *femtozone*. When handsets enter the femtozone, they attach to the femtocell, if authorized to do so; when handsets leave the femtozone, they are handed off to the macro network. By properly configuring the location and transmission power of the femtocell, the femtozone can be made to roughly coincide to the area of the home. In this way, since the femtocell is aware of which handsets are camping on it and which are not (each handset is associated to a specific family member), the femtocell can provide a strong notion of presence: in other words, the femtocell always knows “who is home and who is not.” This knowledge can be used as a trigger for a variety of new multimedia and communications services.

It is interesting to note how the location information provided by the femtocell differs in nature from what is achievable using other location-based mechanisms such as GPS. With GPS, the handset actively tells the network its location. GPS is therefore ideal for services where the user actively “checks in” his/her location with an application, for example to find out information regarding a certain location that the user happens to be in. On the contrary, with femtocells, the handset is totally passive as far as location indication is concerned, and the location information is simply a by-product of the handset entering the femtozone. Femtocells are therefore most naturally suitable to discover handsets entering a predefined area of interest, such as a home or a business, without burdening the handset with such a task. From this discussion, it is rather straightforward to see how location services may use both GPS-based and femto-cell-based location information for different purposes and in a complementary fashion.

3. Unique Traits – B: Seamless Connectivity

The femtocell can act as a bridge between the mobile devices and all the other devices in the home network, and establish seamless connectivity between them. This capability relies on two key features that can be implemented in the femtocell:

i) Local Break Out (LBO); and
ii) Remote Break In (RBI).

LBO applies when the handset is *in the femtozone*. In this case, the femtocell filters the traffic from[to] the handset destined[originating] within the home network. With LBO, the femtocell locally terminates the wireless connection and inspects the packets. Those packets that are not destined to local addresses in the home network are repacked and sent to the core wireless network, while those that are locally destined are extracted and sent directly to their destination within the home network.

For LBO to be at the basis of useful services, the femtocell needs to discover the local devices on the home network. This may be accomplished in conjunction with the home router or home gateway and typically uses existing home networking protocols such as DLNA or Bonjour. With this capability, the handset may directly connect to other devices in the home network and *the connectivity may be created seamlessly* by the femtocell simply as a result of the handset entering the femtozone.

To further facilitate seamless communication, the femtocell may provide additional functionality. For example, the femtocell may provide *DLNA proxy* functionality, through which a “DLNA proxy entity” of a non-DLNA handset is automatically instantiated in the femtocell (again, simply as a product of the handset entering the femtozone). In this way, the handset can be made to “look like a DLNA device” to all other DLNA devices in the home network, thus creating direct communications between heterogeneous devices that would otherwise not be able to communicate. In this context, the femtocell may also provide other types of protocol support to the handset, such as printer drivers (for example, to allow a handset to directly access a printer in the home), transcoding functionality (for example, to properly play back on an handset video content from a home DVR), etc.

The effect of all this capability to the users is that their handset transparently becomes an intrinsic part of the home network the moment they enter the home, which enables a number of very interesting services, as discussed in Section 5 below.

Conversely, RBI applies when the handset is *away from the femtozone* and is attached to the macro network. In this scenario, the femtocell acts as an *anchor* for a tunnel that can be automatically established, starting from the handset – through the macro RAN, the core wireless network, and the Internet – all the way to the femtocell. Since the femtocell is part of the operator network, and the handset is also attached to the macro operator network, the discovery of the two end points of this tunnel is relatively simple. RBI typically requires a server in the network and the implementation of mechanisms such as ICE (or other conceptually similar protocols) to allow firewall traversal into the home network.

It is interesting to note the difference between remote access provided by the femtocell and similar remote access capabilities provided by certain existing commercial applications and devices. With RBI, the femtocell acts a *"universal anchor"* for the remote tunnel that effectively creates a Virtual Private Network into the home network and can be used directly to make any application "remotely capable." On the contrary, with existing remote access applications, the remote capabilities are intrinsic part to the applications themself.

Even more importantly, the role of the femtocell in guaranteeing seamless connectivity both in the home and away from home is further enhanced when combined with presence information, making the femtocell able to switch back and forth from LBO to RBI connectivity *transparently* to the user as the handset enters or leaves the femtozone.

In this way, the user is always connected to the home network: directly, through LBO, when at home; and via a tunnel, through RBI, when away. The powerful combination of LBO and RBI enables the creation of immersive user experiences that can be seamlessly portable from the home environment to the mobile environment.

4. Unique Traits – C: Managed Services

The femtocell is the only device in the home that is managed by the mobile operator. This translates into the opportunity of providing superior services in two dimensions:

i) *Quality of Experience*. Since the operator has control of the device, it can offer packages of services that "work right out of the box," rather than let the user figure out how to install applications across multiple devices. The operator can also make sure that the applications in a package operate well together, have common look and feel, and achieve a consistent experience across multiple devices. Finally, the operator can use the femtocell to achieve a desired quality of service across the applications.

ii) *Security*. The femtocell acting as a bridge between handsets and home network, while very appealing, also introduces a security concern, since a new "door" is potentially opened into the home network and the operator network. However, the femtocell can guarantee that the solution is secure, while allowing authorized users easy access to the new services, by taking advantage of the existing security mechanisms applied to the air interface and creating a secure environment for the applications to run on the femtocell itself.

5. Femtozone Service Examples

In this section, we describe a few representative examples of femtozone services. We limit ourselves to consumer services, but similar femtozone services targeted to the enterprise exist. The intention here is not to be exhaustive, but to offer a few simple examples of the type of services that can be enabled by the unique characteristics of the femtocell.

Consumer femtozone applications can be divided into two broad classes:

i) Family Communication Applications: and
ii) Multimedia Femtozone Applications.

The *Familly Communication Applications* use the presence capabilities of the femtocell to create new ways to keep the family connected. This category can be further subdivided into several classes:

- **Alert Services.** Perhaps the most typical example of femtozone application is a service whereby the femtocell, when a specific handset enters or leaves the femtozone, automatically sends a SMS or email message to a pre-configured handset attached to the macro network. This simple service is useful, for example, to automatically notify the parents at work that their children came home safely from school. A similar service posts the notification that a user is now at home on a Social Networking website. Yet another variant is a *reminder service*, whereby the femtocell sends a message to a certain handset as it leaves the femtozone (e.g., "Did you lock the door?"). Another application in this category is the *Sticky Note* service, in which a family member generates a note for another family member, which is displayed on the corresponding handset (or on another device in the home) when that family member comes home (e.g., "Please turn on the oven").

- **Enhanced Telephony**. An interesting service in this category is the *Virtual Home Number* (VHN), in which an incoming call to the VHN rings all the cell phones in the house. With this service, the cell phone behaves like a cordless phone when in the home, but with all the advantages of the consumer being able to use a single device. This service may be further enhanced by combining it with other PBX-like features, such as intelligent routing of an incoming phone call to the handset(s) which have that incoming phone number as part of their contacts. This intelligence uses the fact that the femtocell interacts with the handsets of all family members, can read their contact lists, store them, and use them for directing the call. Other useful features that are relatively simple to implement by taking advantage of the femtocell are *device shifting*, where for example a call is transferred from a mobile handset to a wired speakerphone, and *conferencing*, where additional parties in the home are added to an ongoing conversation.

- **Family Intercom, Broadcasting, Localized Push-to-Talk (PTT).** The femtocell may set up calls within devices in the house. This does not necessarily have to be limited to mobile handsets, but may also include VoIP phones, soft-clients running on the laptops of family members, etc. The experience that is created can also be that of an Intercom to easily communicate among family members in different rooms in the house. The femtocell can even provide broadcasting capabilities to different devices in the house (e.g., “Dinner is ready!”). Similarly, the femtocell may locally provide PTT service among the handsets in the home.

- **Multi-Device Interaction**. The fact that the femtocell can interact with both mobile and home devices opens some interesting possibilities for services that combine different devices. One example in this category is a service that displays the call id of an incoming call on a TV screen, so a user in front of the TV can decide whether to answer a call or not without having to reach the phone.

The *Multimedia Femtozone Applications* take advantage of LBO, RBI, and related functionality in conjunction with presence to enhance the way consumers interact with their media. Also this category can be further broken down into several classes:

- **Content Synchronization**. A typical service in this class is the automatic synchronization of content (pictures, videos, etc.) on the handset with some other device in the home network or with a server in the WAN as the handset enters the femtozone. The content can be seamlessly played back on a device in the home (e.g., pictures from the handset can be shown on the TV) or backed up to a storage device. Also in this class are services where the handset synchronizes with a content repository every time it comes back to the femtozone, so the user has always fresh content on his/her handset. Another interesting service is the *Family Calendar*, where the calendars in each handset in the family synchronize with an application running on the femtocell, which in turn produces a consolidated version of all the calendars.

- **Remote Access and Place-shifting**. These services stream or download content from devices in the home to handsets attached to the macro network. Because of the ability of the femtocell to interact with all devices in the home, compelling functionality such as *pause and resume* on a different device is relatively simple to achieve. Because of the transparency advantage of RBI over existing remote access applications, as noted above, these femtozone services often achieve superior user experience. An important vertical in this category is *Home Surveillance* and *Home Control*. An example in this area is an application that automatically turns on/off air conditioning or some other appliance as the user enters/leaves home.

- **Personalization.** Since the femtocell can distinguish the presence of individual family members, it can enable highly personalized service experiences on multiple devices (for example, customized personalities to handsets or other devices when the users are in the home), as well as specific personalized applications such as Parental Control.

6. Vision and Challenges

Due to their obvious potential consumer appeal, femtozone services are rapidly becoming an important part of the femtocell business case for operators worldwide. Although a few operators have already started preliminary deployments of some simple femtozone services (e.g., the alert services), a lot still has to happen in the industry to make femtozone services live up to their full potential.

As described in the previous section, femtozone services often rely on interactions between multiple devices orchestrated by application components running on the femtocell (or on devices attached to the femtocell). Femtozone applications may in fact have application components running on several nodes, including femtocells, handsets, home devices, home gateways, web clients, and network application servers.

A necessary ingredient to foster the development of femtozone services is the creation of a suitable environment on the femtocell to accommodate and run these services, and provide:

- **To Application Developers**. A development environment that exposes the unique capabilities of the femtocell to the application layer through convenient APIs, while hiding the internals of the femtocell must be created. This environment needs to make the femtocell capabilities available not only within the femtocell, but also to the other nodes that may be involved in the application. In particular, the handset needs to be made *femtocell aware* at the application layer by augmenting the existing capabilities of the handset OS.

- **To Operators.** A suitable deployment environment for the new services that augments the existing operator's service delivery platform must be provided. This delivery platform must enable unified provisioning, updating, and accounting of the new applications, must guarantee security, and ensure consistent performance of the applications.

To attract third-party application developers and create an ecosystem of femtozone services, it is crucial that such a femto-capable environment uses *standard, open APIs* so that applications can run across femtocells of different vendors. The Femto Forum, the primary industry organization devoted to promotinging femtocell deployment, has been spearheading the effort of creating such a common framework for femtozone services and defining common femtocell-specific APIs in the femtocell, in the handset, and in the network servers. The Femto Forum plan is to then liaison with the relevant standard bodies to drive standardization where necessary.

Once this infrastructure is in place, there is little doubt that the femtocell will play an important role in the digital living room of tomorrow.

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Femtocell Networks: Perspectives before wide Deployments

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Abstract
Femtocells have started to be commercialized. They are a very cost effective solution for operators, in order to support the increasing traffic demand of their customers, due to the evolution of mobile phones as well as the development of new multimedia services. However, before wide femtocell deployments will occur, a number of challenges still have to be solved and in particular self-organization is a major concern. Once these challenges are solved, femtocells are expected to be deployed not only inside home, but also in enterprises and hotspots.

After a brief introduction on the state of the art on femtocell deployments in Section 1, major technical challenges will be investigated in Section 2. Section 3 will focus more on self-organization and finally Section 4 will give perspectives related to the most important scenarios.

1. Introduction

In order to propose new mobile multimedia services to their customers, such as video on demand, web2.0 services or new applications, cellular operators are currently seeking new solutions to improve the capacity of their network. Moreover, an optimal solution to increase the capacity of the network is to extend the radio coverage. Hence operators are more and more interested to deploy specific devices (see Fig.1) that will complement the traditional outdoor base stations, a.k.a. macrocells. Hence, future networks will be heterogeneous and based on the use of elements such as relays, picocells and femtocells. Relays are used to retransmit the signal due to the macrocells and concentrate it in specific areas, whereas pico/femto cells are new small base stations directly installed in "dead spots", thus offering great capacity and coverage improvements. A major advantage of femtocells compared to relays or picocells, is that they do not need to be planned and maintained by cellular operators, because they are connected to the network operator via Internet. Therefore, femtocells [1], which are deployed by the end-customers without any human supervision, are a very cost effective solution for operators. Femtocell deployments have been launched since 2009 and at the date of July 2010 there was already 13 commercial launches all over the world. The *Femto Forum* [2], which gathers more than 100 cellular operators and equipment manufacturers, works on the standardization of femtocells as well as their promotion. However, femtocells are still in their early development stage, and this is why they are not widely deployed yet. Moreover, the use of dual mode handsets such as iPhones (including a WiFi air interface) is nowadays very common; hence operators and companies promoting femtocell technologies are seeking new advantages and applications in order to attract customers. Finally, there are still a few technical challenges to be solved before large scale deployments will occur as will be described below.

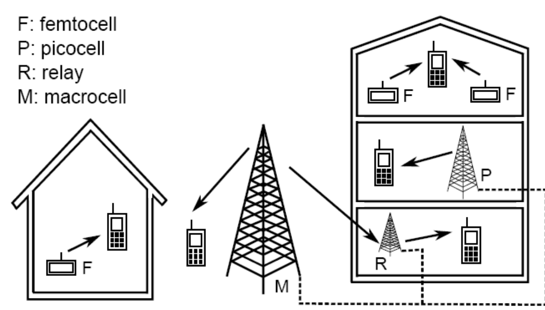

Fig. 1. Example of heterogeneous network deployment with macrocells complemented by relays and pico/femto cells.

2. Major Technical Challenges

Cellular operators and femtocell manufacturers have to face four main technical challenges:

- **Interference.** It is easy to understand that femtocells can interfere with the other macrocells, but also between themselves. For initial deployments, interference can be easily reduced by deploying femtocells and macrocells in different carriers. In such case macro/femto interference is avoided, whereas femto/femto interference is not a major concern because the number of femtocells is not high yet. However, much more femtocells are expected to be deployed in the near future. Therefore co-channel deployment (where femtocells and macrocells share the spectrum), which offers better performance, should be implemented. It is to be noticed that interference can be efficiently mitigated only if both the radiated power and frequencies are efficiently allocated between the cells.

- **Mobility.** When many femtocells are deployed, it is expected that mobile users will have to handover very often. Furthermore, the fact of performing regular handovers from cells to cells has two drawbacks: First, it increases the signaling in the core network of the operator, which may reduce the performance of the global network. Second, it increases the chances of unsuccessful handovers, especially because of the IP backhaul which can suffer delays, and because of the lists of neighboring cells which may be difficult to regularly update due to the high number of cells. That is why it is crucial that the handover parameters as well as the neighboring lists are optimally chosen depending on the conditions.

- **Access Control.** Three access control mechanisms have been standardized in 3GPP: *open access* where all the users are allowed to connect to all the femtocells without restrictions, *private access* a.k.a. closed subscriber group (CSG) where only a list of predefined users can connect, and *hybrid access* where part of the resources are open, whereas the other part is in CSG mode. Hybrid access may be an optimal approach because it keeps the advantages of open access where interference is easier to mitigate and CSG where the customers who pay for femtocells are ensured to have high performance. However the choice of the ratio of open/CSG resources has to be adapted and depends on the deployment scenarios.

- **Synchronization.** It is necessary that femtocells, which are not maintained by an operator, can synchronize with the other cells. In particular, the synchronization of the oscillator is important in order to avoid frequency drifts that would lead to possible interference as well as unsuccessful handovers. Hence recent solutions based on sensing of neighboring cells, as well as sensing from the backhaul, and use of GPS signals. Moreover recent solutions include advanced GPS receiver or TV receiver especially optimized for time synchronization and more efficient to penetrate inside buildings.

3. Self-Organization: the Solution for Large Scale Deployments.

As detailed in the previous section, parameters related to interference avoidance, mobility, access control or synchronization, will have to be chosen depending on the conditions, e.g., the kind of scenario, the number of users, the number of cells, or the traffic demand. That is why before large scale deployment occurs, with millions of femtocells deployed at uncontrolled positions, it is very important that femtocells include more self-organizing network (SON) capabilities. Therefore, SON femtocells will be able to adapt themselves to their environment. In order to perform an efficient self-organization, three main tasks are generally investigated:

- **Self-configuration.** Each time a new femtocell is switched-on, it has to adapt its initial parameters such as radiated power, channels, handover parameters or IP sec tunnel establishment between the femtocell and the core network.

- **Self-Optimization**. When the conditions in the environment change such as traffic demand of the users, femtocells have to regularly change their parameters, in order to improve their performance, while reducing their negative impact of neighboring cells. For instance femtocells can include an idle mode, where femtocells will reduce their radiated power when nobody makes use of it. Such power reduction is important for interference mitigation.

- **Self-Healing.** Unlike macrocells, femtocells are not maintained by an operator. Hence, in case of unexpected events, it is necessary that femtocells can react quickly and correct the problems. For instance in case of failure of a neighboring cell, femtocells should be able to detect this failure, in order to redirect the traffic to another cell.

SON femtocells are challenging but necessary for large scale deployment, that is why most of the research is currently focusing in this direction. In 3GPP little work has been done in this area such as scanning of neighboring cells or idle modes. However, and in particular when LTE networks will start to be widely deployed, SON will be very important that is why 3GPP Release 10 and the following versions have an important focus on self-organization. Finally, if more SON capabilities are implemented in femtocells and offer acceptable performance, it is expected that femtocells will be deployed in many scenarios. Therefore, they will not be only aimed at the home market, as it is mainly the case today, and new scenarios will appear, offering huge possibilities for operators.

4. Deployment Scenarios: from Home to Hotspots.

Depending on the environments where they are deployed, femtocells have different characteristics. In this section, the major deployment scenarios are presented in historical order as the large deployments are expected to occur.

- **Home femtocells**. As explained before, home femtocells, a.k.a. home Node-B (HNB) are already commercialized for 2G and 3G. Interference between femtocells is not a concern yet, and most of current deployments are either in open or CSG access. If current home femtocells are only aimed at improving the radio coverage inside homes where data rate was not sufficient, operator and manufacturers are currently developing new applications, whose aim is to attract more customers. Indeed the use of smart phones supporting WiFi is the major competitor of femtocells, hence *connected home* applications (where the femtocell becomes a central point to control the equipment inside the home such as TV, HiFi, etc.) and *femtozone services* (applications that are automatically activated when a user enters inside his house) are already available but there is no standard development API yet. However, such standardization is currently under investigation by *Femto Forum* and an API will be soon available for developers.

- **Enterprise femtocells**. Deploying femtocells in small companies (where the number of cells is not huge, i.e., no strong planning is needed) is a very cost effective solution for improving capacity in enterprises and office buildings. In such scenario, interference between cells has to be mitigated. Hence, SON is ever more important, and for instance power control which reduces the overlap between the cells and adapt it to the movements of the users is needed. Also the access control may have to be adapted, depending on the presence or not of guests in the company. For instance, they may be configured to leave only a small amount of resources for guests, in order to always ensure a high throughput for their staff. Enterprise femtocell chipsets are under development, and the main difference compared to home femtocells is the number of supported users which has to be higher. Currently, chipsets on the markets can support up to 64 users (whereas 4 to 6 users is sufficient for home femtocells). Of course enterprise femtocells, in order to compete with picocells, have to include effective SON capabilities, as well as being manufactured at low costs.

- **Hotspot femtocells**. When the problem of SON will be solved, and due to their low cost, as well as self-maintenance, femtocell may be deployed in larger scenarios and may be the most cost effective solution for covering complex scenarios such as underground, airports and shopping centers. Such femtocells, deployed in open access mode, will be deployed in a similar manner as WiFi nowadays. Moreover, the idea of installing femtocell outdoors is often discussed since it may be a very cheap option for filling dead spots in urban areas. However, with such outdoor urban femtocells, the challenges are not only related to SON capabilities which has to be very efficient, but also on the backhauling which is more complex outdoors, as well as the manufacturing cost. In Table 1, the characteristics and properties, depending on the previous scenarios are summarized.

It is to be noticed that, before wide deployment occurs, and in order to solve the remaining challenges, a possible approach is to use indoor radio network planning tools. Such software with 3D building modeling, radio signal prediction and interference evaluation capabilities, e.g., iBuildNet [6] can help to study specific scenarios and evaluate the impact femtocells will have on the macrocell layer, as well to test the SON algorithms before their implementation.

Table 1. Main properties and challenges depending on the scenarios.

	Home	Enterprise	Hotspot
Num of femtocells	1	many	many
Access control	CSG or hybrid	hybrid	open
Handover	femto/ macro	femto/ macro and femto/femto	femto/ macro and femto/femto
Major Challenges	new applica-tions	SON, Support high capacity	Outdoor IP Backhaul, Cost

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References

[1] J. Zhang and G. de la Roche, "Femtocells: Technologies and Deployment". John Wiley & Sons Ltd, January 2010.
[2] Femto forum, http://www.femtoforum.org.
[3] I. Guvenc, M. R. Jeong, F. Watanabe, and H. Inamura, "A Hybrid Frequency Assignment for Femtocells and Coverage Area Analysis for Co-Channel Operation", IEEE Commun. Lett., vol.12, no.12, pp. 880-882, Dec. 2008.
[4] D. Lopez-Perez, A. Valcarce, G. de la Roche, and J. Zhang. "OFDMA Femtocells: A Roadmap on Interference Avoidance". IEEE Communications Magazine, 47:41–48, September 2009.
[5] Ashraf, H. Claussen and L.T.W. Ho. "Distributed Radio Coverage Optimization in Enterprise Femtocell Networks". In IEEE International Conference on Communications (ICC), May 2010.
[6] iBuildNet – In-Building Network design tool, Ranplan, http://www.ranplan.co.uk

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Green, Cost-effective, Flexible, Small Cell Networks

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1. Introduction

During the last century, the amount of information that can be exchanged within a given area over a slice of the useful radio spectrum has doubled every 30 months [1]. Without doubt, this tremendous increase in spectral efficiency was rendered possible through the development of sophisticated coding and modulation schemes, efficient channel access protocols and the broadening of the usable radio frequency spectrum. However, the by far biggest capacity gains in personal communications are due to an increasing network densification, i.e., universal frequency reuse and the shrinking of cell sizes.

The almost ubiquitous high-bandwidth coverage and the advent of smart-phones and other portable devices have led to mobile data traffic surpassing voice on a global basis [2]. Several market forecasts, e.g. [3], predict an exponential increase in mobile data traffic during the years to come. This development will be driven mainly by new, uniquely mobile applications (navigation, social networking, video telephony, etc.) being rich in multimedia content and increasing mobile-broadband substitution through smart phones and USB-dongles.

In the light of this rapid change, it is justified to ask how operators will satisfy the exploding demand for more and more bandwidth. Mobile networks are a mature technology with little technological breakthroughs in coding/modulation schemes to be expected in the near future. Moreover, there are hardly any additional spectrum resources with desirable propagation characteristics available. Therefore, interference cancellation techniques [4], cooperative communications schemes (network MIMO) [5] and cognitive radio [6] are subject of current research seeking to further improve the way the available spectrum is utilized. However, none of these techniques can carry the forecast traffic increase alone without a further network densification. While the acquisition and the planning of new macro cell sites, especially in dense urban areas, become increasingly difficult and expensive (CAPEX), the deployment, operation and maintenance of additional macro cells cause heavy operational expenses (OPEX). Thus, operators are likely to face a “wall” in the future where a further network capacity-increase through additional macro cell deployments causes prohibitive costs.

“Small cell networks” (SCN) are founded on the idea of massive network densification by using base stations (BSs) that are substantially smaller than traditional macro cell site equipment. The deployment and profitable operation of SCNs is rendered possible by sharing already existing sites and backhaul infrastructure with other wireline/less access points (e.g., FTTN/H or VDSL street cabinets, DSL backbone) and by relying on autonomous operation and self-configuration. Eliminating the need for further cell site acquisition and detailed network planning, SCNs can thus drastically reduce CAPEX and OPEX while ensuring high data-rates, uniformly delivered over the coverage area.

2. Small Cells

The general term “small cell networks” covers a range of radio network design concepts which are all based on the idea of deploying BSs much smaller than typical macro cell devices to offer public or open access to mobile terminals. In essence, a small cell BS can be seen as a cellular BS designed to serve a limited coverage area, around a factor 100 smaller than a traditional macro cell. A small cell BS is a small, humanly-portable, low-cost and low-power device. It can be deployed in a plug-and-play fashion, self-configures all necessary parameters and does not require any regular maintenance. Small cells (SCs) target a coverage radius of 50−150m and radiate at low power (0.1-10W). Possible deployment scenarios are public indoor and outdoor with open or closed access, e.g. in small boxes on existing street furniture, metro hotspots, etc., but also residential and enterprise environments. In this regard, SCNs also comprise low-power micro, pico and femto cells.

The main benefits of SCNs are:

- SCNs allow to offload traffic from the macro cell and to provide dedicated capacity to homes, enterprises or urban hotspots, i.e., where most data usage occurs. SCNs can be

seen as a low-cost coverage extension under umbrella macro cells, but might also replace them gradually.
- Dense SCNs allow for unprecedented mobile system capacities (in terms of Gbit/s/km^2) and higher data-rates for each user since less devices share the bandwidth of a single cell.
- SCNs have the potential to reduce the ecological footprint of cellular networks. Bringing mobiles and BSs closer together leads to less required transmit power and enhances the terminal's battery duration. Moreover, owing to their reduced transmit power, small cells minimize the threat to human health compared to macro BSs.
- SCNs make cell site rental and dedicated backhaul provisioning superfluous since they rely on already existing backhaul infrastructure (FTTN/H, DSL) and are integrated in the street furniture, enterprise buildings or people's homes.
- Self-organization and optimization of the devices allows for plug-and-play deployment, requires no network planning and reduces maintenance costs.

3. Technical Challenges

There are several technical challenges related to the large scale deployment of small cells which we will outline in this section. First of all, today's wireless cellular networks require an extensive involvement of human operators for planning, configuration, operation, management, monitoring and maintenance, which causes huge operational costs that amount easily to more than 75% of the total expenses. Therefore, any massive network densification necessitates a significant degree of autonomy, self-configuration and optimization of its components to keep the operational expenses low. Ideally, similar to femto cell equipment, small cell BSs could be installed in a plug-and-play fashion without requiring any further initialization steps and maintenance. Experiences from existing femto cell deployments could provide valuable insights in this regard. Among the most important issues related to self-configuration and self-optimization are:

- (dynamic) configuration of radio parameters
- resource allocation (time, frequency, power)
- interaction/coexistence between small cell BSs and the macro cell layer
- optimization of joint area coverage
- authentication, registration and access permission
- automatic discovery of neighbors and composition of optimal neighbor lists
- intelligent handoff (SC-SC, SC-macro cell)
- self-protection and network recovery
- scalability (to possibly 100k's of devices)

Second, since a SCN is by definition not planned and the BSs are likely to be installed at sub-optimal locations, it is difficult to ensure full coverage without the help of some macro cells. Also indoor coverage from outdoor SCs might be difficult to achieve. Moreover, the low BS antenna heights make it difficult to model the radio propagation in urban areas with possibly strong line-of-sight (LOS) components. Thus, coverage prediction and the calculation of optimal cell sizes require extensive ray-tracing simulations based on 3D building shape data bases.

Third, regular hard handover (HO) mechanisms are not suited for SCNs due to their small coverage range. For fast moving terminals, HOs would occur far too often to allow for enough time for network scanning, ranging, etc. Location management techniques and routing algorithms for highly mobile SCNs also pose an important technical challenge.

Fourth, due to security aspects it is of utmost importance to identify vulnerabilities of SCNs. On account of its hierarchical flat structure, a SCN might exhibit weak points unknown to date in traditional cellular systems. For example, user privacy is at risk since most of the user traffic passes through an IP-based backhaul network which might be not under full control of the operator. The small cell equipment must also be tamper-resistant to prevent hackers from getting access into the small cell BS. Also self-healing mechanisms in case of BS failures need to be developed.

Fig. 1. Deployment scenario of a small cell network

4. Vision & Tools

SCNs are a promising concept to cater for the future needs of mobile communication systems. However, to tap their full potential, the way we build and think about wireless networks needs to be radically changed. Our vision is green, cost-effective, flexible and cooperative SCNs (see Fig. 1): SCNs could become a green technology which reduces the carbon footprint of wireless networks. This is because small cell BSs require less transmit power and could be made independent from external power supplies, for example through energy harvesting mechanisms like solar panels. In addition, if equipped with satellite backhaul links, SCNs could also be deployed in remote areas or developing countries where a lack of reliable power supply and infrastructure renders a classical macro cell deployment impossible. However, the large scale deployment of SCNs is only ecologically worthwhile if new energy efficient protocols and power saving mechanisms are adopted. Given the large number of devices in a SCN, it is likely that many small cells are not actively serving users but rather wasting energy due to a lack of stand-by or sleep modes.

We see SCNs as dense, self-organizing, self-healing and secure networks where mobiles and BSs interact and self-adapt in an intelligent manner with only a limited amount of human intervention. They can be seen as a bridge between fully centralized and fully decentralized networks, differing from ad-hoc networks through a static “infrastructure” of small cell BSs. By supporting a multitude of different standards (W-CDMA, WiMAX, LTE, Wi-Fi, Bluetooth, etc.) and by being able to transmit/receive on different frequency bands, a SCN could schedule data traffic according to the most favorable technology and also support legacy devices.

Cooperation between the small cell BSs is mandatory for any form of self-organization and mobility management. Due to their small coverage range, HOs between small cells would occur far too frequent in highly mobile environments and new forms of handovers must be considered. A possible solution consists in the formation of “virtual cells”, i.e., clusters of cooperating cells. A virtual cell is a group of BSs seen by the mobile as a single distributed BS. Inside a virtual cell, a mobile can move without performing regular HOs. Only at the virtual cell boundaries a HO is performed.

Making SCNs a reality requires interdisciplinary research which comprises many different tools of which we will mention a few:

- **Large random matrix theory (RMT):** The study of SCNs involves both a large number of communicating/interfering devices and wireless channels with a different path loss between different devices and possibly strong LOS components. Since these channel models are hard to tackle analytically for finite dimensions, the study of asymptotic limits provides useful bounds and insight into the most crucial performance parameters.

- **Game theory (GT):** Ideally, the small cell BSs act as autonomously as possible with limited feedback and control. Thus, there is a need for decentralized optimization algorithms. Open questions are, e.g., the optimal size and grouping of virtual cells. Coalition games [7] provide a useful framework for this setting.

- **Interference alignment (IA) and VFDM:** The co-existence of SCNs, macro cells and possibly other (un-)licensed networks requires novel strategies for interference mitigation. Promising candidates are interference alignment [8] and Vandermonde frequency division multiplexing (VFDM) techniques [9].

- **Stochastic geometry:** An often neglected aspect in the study of wireless networks is the impact of the distribution of the terminals and BSs. The rather novel field of stochastic geometry [10] might provide answers to the questions of the optimal small cell density and the impact of (clustered) random versus regular (e.g., hexagonal grid) network topologies.

References

[1] W. Webb, “Wireless Communications: The Future”, Wiley, 2007.
[2] Ericsson, “Mobile data traffic surpasses voice.” [Online]. Available: http://www.ericsson.com/thecompany/press/releases/2010/03/1396928
[3] Cisco, “Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2009-2014,” White Paper, 9 February 2010. [Online]. Available: http://www9.cisco.com/en/US/netsol/ns827/networking_solutions_white_papers_list.html
[4] J. Andrews, “Interference Cancellation for Cellular Systems: A Contemporary Overview,” *IEEE Wireless Communications Magazine*, vol. 12, no. 2, pp. 19 – 29, Apr. 2005.

[5] D. Gesbert, S. Hanly, H. Huang, S. Shamai, O. Simeone, and W. Yu, “Multi-cell MIMO Cooperative Networks: A New Look at Interference,” *IEEE J. Sel. Areas Commun.*, 2010, to appear.

[6] J. Mitola, G.Q. Maguire Jr., “Cognitive Radio: Making Software Radios More Personal,” IEEE *Personal Communications*, vol. 6, no. 4, pp. 13–18, Aug. 1999.

[7] W. Saad, Z. Han, M. Debbah, A. Hjørungnes, and T. Basar, "Coalitional Game Theory for Communication Networks: A tutorial," *IEEE Signal Processing Magazine*, vol. 26, no. 5, pp. 77-97, Sept. 2009.

[8] V.R. Cadambe and S.A. Jafar, "Interference Alignment and Degrees of Freedom of the K-User Interference Channel," *IEEE Trans. Inf. Theory*, vol.54, no.8, pp. 3425-3441, Aug. 2008.

[9] L. Cardoso, R. Calvacanti, M. Kobayashi and M. Debbah, "Vandermonde-Subspace Frequency Division Multiplexing Receiver Analysis," PIMRC 2010, Istanbul, Turkey.

[10] M. Haenggi, J. G. Andrews, F. Baccelli, O. Dousse, and M. Franceschetti, “Stochastic Geometry and Random Graphs for the Analysis and Design of Wireless Networks,” *IEEE J. Sel. Areas Commun*., Sept. 2009.

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Next Generation Femtocells: An Enabler for High Efficiency Multimedia Transmission

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Abstract
The first generation of femtocells is evolving to the next generation with many more capabilities in terms of better utilisation of radio resources and support of high data rates. It is thus logical to conjecture that with these abilities and their inherent suitability for home environment, they stand out as an ideal enabler for delivery of high efficiency multimedia services. This paper presents a comprehensive vision towards this objective and extends the concept of femtocells from indoor to outdoor environments, and strongly couples femtocells to emergency and safety services. It also presents and identifies relevant issues and challenges that have to be overcome in realization of this vision.

1. Introduction

Femtocells are already appearing in the market for some specific applications such as coverage hole fillers. Nevertheless their true potential is yet to be fully exploited. On one hand they provide fixed-mobile convergence, thereby bringing several benefits to the end user such as ubiquitous service provision, and also to the mobile cellular operator such as off-loading the load on macro network, better indoors coverage, better spectral efficiency through small cell-sizes and of course capturing a portion of the fixed-line market. They can also act as a true enabler for high efficiency multimedia transmission such as next generation high definition (HD) streaming that requires very high data rates and constrained delay performance. Existing systems can start to support multimedia traffic, however they are limited to low numbers of users, situated close to basestations, and with low mobility. Theoretically femtocells enable the whole capacity of a sector/cell inside user premises (practically it would depend upon efficiency of interference management between macro and femto network) assuming enough capacity is available on the wired backhaul, which is not a major problem given the advances in wire line technology. According to studies in [1], there has already been a 1600x increase in spectral efficiency since 1957, due to the spatial reuse afforded by reduced cell sizes and transmit distance. With the further reduction in cell size, and additional isolation arising from in-building operation in many femtocell scenarios, this trend is expected to continue, with great benefit for high capacity services such as multimedia. Despite their potential, femtocells still have some issues to overcome such as interference management, latency problems due to backhaul via internet (which is quite important for delay sensitive multimedia services), and handover signalling and multimedia stream routing to support mobility.

In this letter, we present a vision in which femtocells act as a key enabler for broadband multimedia services for both indoor and outdoor environments. We also present associated challenges and opportunities to achieve these goals.

2. Vision

Our vision of femtocells envisage a device or access point that is not only capable of broadband transmission for bandwidth hungry multimedia services but also capable of efficient transmission of low data rates with low duty cycle by way of machine to machine (M2M) communication with machines or sensor nodes in the local neighbourhood. Furthermore, a uniform solution is envisaged by extending the concept of classical femtocells from indoors to outdoors where they could act as fixed or mobile relay stations [2] with the difference that the backhaul is wireless for the latter. Moving femtocells will also address the problem of serving multimedia traffic to highly mobile users. For all these cases, we consider self-organisation (self-x) and self-optimisation to be an integral feature of femtocells as the scale of their deployment could be huge and without self-x operation the network management, optimisation and its evolution would simply not be feasible. Fig. 1 illustrates the above described vision with some examples from real life and shows that the femtocell is not only providing high efficiency interactive and HD streaming multimedia services

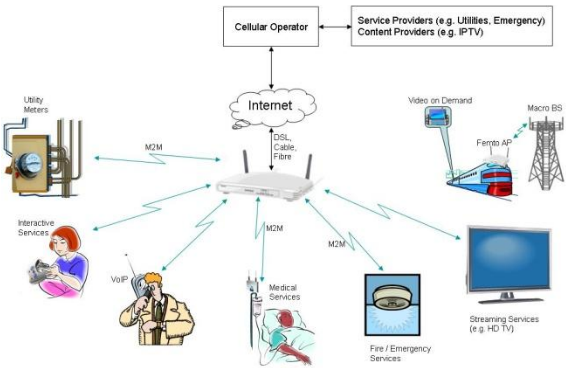

Fig. 1. Vision

but can also have M2M communication for various applications such as utility meter readings and automatic transmission to the utility provider, interface with the fire alarm and in case of a fire event autonomous communication with emergency services, and communicating the sensor data from a patient to corresponding medical services. Infact, femtocells can provide a new paradigm of safety and emergency services such as requesting multimedia rich feedback and rapid reaction beyond, for example, a typical simple localization service. This is particularly important for the care and safety of vulnerable persons such as elderly people and children.

The vision figure also illustrates the use of femto access points in outdoor areas, for example in moving passenger vehicles for provision of high efficiency video on demand (VoD) services with backhaul through the wide area cellular operator.

3. Opportunities and Challenges from Radio Access Perspective

This section discusses the vision presented in section 2 from radio access perspective.

- **Flexible Air Interface.** Since the presented vision encapsulates transmission of a variety of multimedia data, it implies the air interface should be flexible to accommodate efficient transmission of each. At present, no single air-interface is optimised for efficient transmission of both high speed data (e.g. for broadcast streaming) as well as low speed data for M2M communication. However, for typical home applications, interactive and streaming services are expected to be dominant, thus M2M communication may take place by piggybacking on existing air interfaces such as the 3GPP LTE/ LTE-Advanced air interface that are quite suitable for broadcast and multicast services as well.

- **Interference Aware Resource Allocation.** Since the majority of multimedia services like streaming or interactive gaming are delay-sensitive (which in the case of femto networks is even more critical due to their inherent dependability on the internet), the instantaneous quality of service (QoS) requirements (particularly latency) should be satisfied irrespective of the radio environment. Service degradation is highly likely to happen due to inter-cell interference (ICI) [3]. In femtocell networks, the ICI may originate from other femtocells (co-tier) or the macro cell(s) (cross-tier) in the vicinity. Again due to the delay sensitivity of multimedia traffic, and the nature of the IP backhaul, femtocell schedulers may have to compromise minimal ICI generation in order to meet end-to-end delay constraints. Additionally the high capacity nature of multimedia traffic will tend to increase ICI, unless appropriate techniques are used to limit this. Furthermore, the inherent uncertainty in the topology of the network in the presence of unorganized femto access points introduces extra dynamism to the nature of ICI in such networks. Therefore, to support QoS requirements, the resource allocation algorithms should have robustness against this impairment. Towards this objective, some basic characteristics of multimedia services can be combined with different topologies of femtocell networks to meet the demand while inflicting lower total interference on the network. Clusters of femtocells concentrated in different residential / enterprise buildings can provide the necessary platform to adopt such strategies. Here, the available traffic aggregator / gateway [4] within a block can act as the central controller to utilize local ICI coordination strategies like inter-cell power control, dynamic interference avoidance and frequency partitioning. Furthermore, multicasting can be employed to share similar resource blocks among adjacent femtocells with similar streaming demand. These approaches facilitate the migration towards fully decentralized strategies by introducing clustering and local controllers rather than a global entity and in turn lead to less total ICI and better service support in the network.

- **Self-Organisation and Optimisation.** Due to inevitable uncertainty about the scale of femtocell deployments and their dynamic presence creating new challenges, self-x operation is expected to play a key role in their success. Moreover, notice the fact that the current broadband multimedia data transmission has been realized mainly with the recent feasibility of the high-speed mobile internet within a single macrocell. Thus, the feasibility of new potential benefits from the self-x enabled femtocells may lead the evolution of various multimedia services highly demanded in a diverse environment. Specifically, for the multimedia transmission, it can be envisioned that the self-x algorithms for femtocells should be designed to have the following characteristics: minimal signalling overhead, agility to cope with acute dynamics of traffic and environment, full scalability to accommodate large number of nodes in the system and low complexity to enable cost effective practical implementation. Furthermore, in order to meet the high demands of bandwidth hungry multimedia applications, the self-x functions in femtocells need to operate at least on two different time scales with different but complementary objectives: 1) Short time scale with the objective of continuously maintaining optimal resource efficiency in the face of fast spatio temporal dynamics of traffic and environment e.g. by adapting power control, scheduling strategy, opportunistic reuse; 2) Large time scale with objective of focusing the resources where and when needed e.g. by antenna tilting, channel borrowing, load balancing, coverage pattern reshaping. Equipped with self-x features designed within the aforementioned vision, a variety of next generation multimedia services in diverse situations from indoors to outdoors and from fixed to highly mobile environments can become a reality.

4. Opportunities and Challenges from Core Network's Perspective

This section discusses the vision presented in section 2 from core network's perspective

- **Network Architecture**: To connect the femtocells back to the mobile network operator's (MNO) core network, available interfaces used in macrocells can be directly applied to minimize the requirement of equipment upgrading. However, the legacy functional entities originally designed for a limited set of high-traffic macro base stations may not function well for a large number of femtocells with bursty traffic. A femtocell gateway may be optionally deployed between the mobile core network and the broadband network to act as a concentrator [5]. Arising issues are the function splitting, scheduling and aggregation of multimedia traffic at the gateway. IP multimedia subsystem (IMS) provides a generic framework to offer VoIP and multimedia services for fixed-mobile convergence. The integration of IMS functionalities with femtocells needs further investigation [6].

- **Local Breakout**: One of the major benefits of deploying femtocells is brought by the capability of local breakout [7]. With this functionality, not only a direct connection can be created between a mobile handset and a device in the local network, but also the traffic can be exchanged with the Internet without traversing the mobile operator's network at the presence of a local gateway. In a home network, mobile users can exchange music and video with their home PC at a very high speed. In an enterprise network, extension calls and multimedia sharing can be locally enabled. For VoD and VoIP services originating from the Internet, direct IP access can significantly reduce the transmission latency compared to the conventional path via the mobile core network. To support local breakout, effective localized routing and placement of local gateways need to be studied. Other challenges include how to support simultaneous access to both the mobile core network via home routing and the Internet via local breakout, how to trigger local breakout from the MNO side and mobility issues. Other core network based functionality such as authentication, billing/accounting, end-to-end QoS and security may require a hybrid approach with some signalling traversing the core network, while user data is carried over local breakout.

- **Mobility**: Seamless mobility support is one of the key requirements of multimedia communications. The allowed latency for real-time applications is typically less than 150 ms. Whereas functional entities for mobility management may be located in the mobile core network (e.g. mobility management entity (MME) in 3GPP LTE/LTE-Advanced), femtocell access points are deployed on users' premises. They are connected via residential DSL or cable broadband, which may cost up to hundreds of milliseconds for end-to-end transmissions without additional prioritized mechanisms in the Internet. The immediate challenge arising for multimedia communications is how to maintain the service grade during handover from macrocell to femtocell, from femtocell to macrocell and between femtocells - re-routing multimedia streams in a disjoint core network, and keeping them synchronised between different cells is a challenge. For a networked femtocell scenario, local mobility management schemes need to be investigated to deploy functional entities locally such that the signalling does not need to reach the mobile core network. Additionally, there could be increased overheads on the radio access network, with more frequent handover signalling and procedures for mobile users. For a residential scenario, effective handover procedures need to be developed to minimize the impact of handover on the multimedia flows. Furthermore, handover for mobile femtocells is going to be quite challenging for multimedia users. Self-x procedures are expected to play a crucial role in addressing this issue.

- **Quality of Service (QoS)**: IP backhaul plays an important role in femtocell networks, especially for multimedia communications. Current IP backhaul network does not provide guarantees for delay-sensitive traffic. The situation may be even worse when the mobile operator and the broadband operator run independently. The challenges ahead are how to provide acceptable QoS over IP backhaul. The capability of IP backhaul supporting QoS also needs to be taken into account by mobility procedure. For instance, only cells with enough capabilities on their IP backhauls will be considered when the target cell is being selected. Admission control mechanisms need to be implemented at femtocells to maintain the required QoS level.

- **Security**: Effective mechanisms for authorization, authentication and accounting are essential requirements for multimedia communication. Different from binary data security, multimedia content is often of large volume and requires real-time response. Whereas femtocells use the same over-the-air security mechanisms that are used by macrocells, additional mechanisms are needed over the insecure IP backhaul to protect multimedia communication from growing security threats, e.g. denial of service attack and inspection of both signalling and media. Effective authentication mechanisms are also needed to avoid unauthorized access to femtocells and prevent “fake” femtocells collecting user and account details while minimizing their impact on the multimedia performance, e.g. handover latency. As the server for authentication and billing/accounting is normally located in mobile core network, the latency impact incurred by signalling over IP backhaul need to be mitigated.

5. Conclusions and Areas of Further Investigation

This paper has presented a vision in which next generation femtocells play a central role in provision of advanced multimedia services in a variety of daily life scenarios covering the indoor home environment, and outdoor mobile environment, as well as new and unprecedented multimedia support for emergency and safety services. Key issues and challenges from both radio access as well as core network’s perspective have also been identified, that need further investigation in order to fully realise the presented vision. In particular, high latency has been pointed as a key issue not only from scheduling perspective but also from seamless mobility point of view. It is conjectured that self-x operation is expected to play a key role in addressing some of the challenges by smart and intelligent optimisation of radio parameters. Among other issues that could be further studied is to compare femtocells versus broadcast / point-to-region multicast in macrocells for delivery of multimedia, although this comparison will also depend on the service delivery models (e.g. femtocells work better for real "on-demand" delivery, whereas broadcast might work better for scheduled transmissions, with intelligent pre-caching at the receiver).

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References

[1] V. Chandrasekhar, J. Andrews, A. Gatherer, “Femtocell networks: a survey”, IEEE Communications Magazine, Volume 46, Issue 9, September 2008, Pages 59-67.

[2] IST BeFEMTO Project Website: http://www.ict-befemto.eu/ [Accessed online: 22nd July 2010].

[3] N. Damji and T. Le-Ngoc, “Dynamic downlink OFDM resource allocation with Interference mitigation and macro diversity for multimedia services in wireless cellular systems”, IEEE Trans. Vehicular technology, vol. 55, no. 5, Sep. 2006, pp. 1555-1564

[4] 3GPP TR 36.300, “Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN)”, Overall description Stage 2, Release 9

[5] 3GPP TR 23.830: Architecture aspects of Home Node B (HNB) / Home enhanced Node B (HeNB)

[6] 3GPP TR 23.832: IP Multimedia Subsystem (IMS) aspects of architecture for Home Node B (HNB); Stage 2

[7] 3GPP TR 23.829: Local IP Access and Selected IP Traffic Offload.

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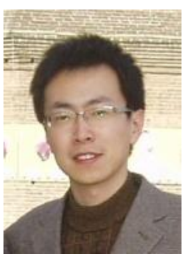

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The Future of Small Cell Networks

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Abstract
Increasing demand for wireless multimedia services is driving strong growth in wireless data traffic. The simplest approach to cope with this growth is reducing the cell size, however with small cells only it is difficult to achieve the required area coverage. Therefore, heterogeneous networks where small cells provide the majority of the capacity and macrocells fill in the gaps to provide area coverage are a promising approach. Today, femtocells have emerged as the first step towards such a deployment model. This paper discusses the challenges and future directions of such small cell deployments.

1. Introduction

The idea of small cells has been around for quite some time [1]. Initially, “small cells” was the term used to describe the cell size in a metropolitan area, where a macrocell (of the order of kilometers in diameter) would be cell split into a larger number of smaller cells with reduced transmit power, known today as metropolitan macrocells or microcells. These cells have a radius of a few hundreds of meters. In the 1990’s cellular picocells appeared [2] with a cell size of between a few tens of meters to around a hundred meters. These “traditional” small cells are used for capacity and coverage infill, i.e. where macro penetration was insufficient to give a good connection or where the macrocell was at its capacity limit. Moreover, these types of small cells are essentially a smaller version of the macro base station. They have to be planned, managed and interfaced into the network the same way as macro base stations. This last point alludes to why small cells (other than metropolitan micro cells) have not gained in popularity. Essentially, the costs associated with deploying and running a large number of small cells outweighed the advantage that this kind of cellular topology provided.

However, new thinking on deployment and configuration of cellular systems in the early part of this century, for example [3][4], began to address the operational and cost aspects of small cell deployment. This thinking has been applied successfully to residential femtocells where the kinds of cost issues mentioned above are amplified. This type of small cell is fundamentally different from the traditional forms in that there is much more autonomy and intelligence in the cell. Additionally, the interfaces back to the cellular network need not conform to the current cellular standards.

In parallel with the need to provide cellular coverage infill for residential use, there are other reasons why there is renewed interest in small cells. Among these reasons are that cellular data and more generally mobile data have become popular, and that this demand will be driven further by future multimedia services. Furthermore, terminals (smart phones) are now commercially available that are able to deal appropriately with this data and are of adequate size and functionality. This increase in mobile data activity has raised some additional questions such as: i) what technologies and cellular topologies can best service the sorts of data demands that we will see in the future and, ii) what is the most energy efficient topology that can deal with this data demand. The importance of these questions is highlighted in Figure 1 where the projected increase in network traffic and its contributing components for North America from 2007 to 2020 is shown [5]. The point made by this figure is that that traffic is set to grow exponentially over the coming years and that wireless data is increasing the most rapidly. Admittedly, it is not the dominant form of traffic but because wireless transmissions are through a hostile environment, it is the most energy consumptive method of data transmission.

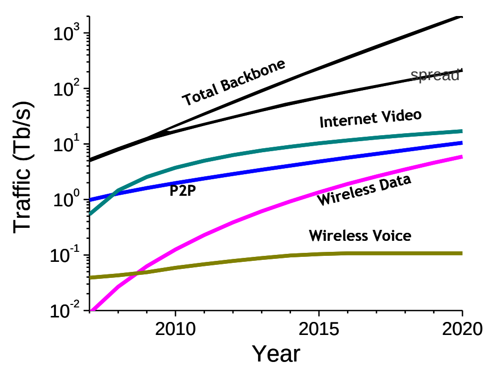

Fig. 1. Traffic demand for North America [5]

Fundamentally the simplest way that physics allows to increase capacity is to reduce the cell size. However, satisfying this demand with a traditional small cell and macrocellular network only will become very expensive (because of limited spectrum availability and operation expense). Fortunately small cell technology has moved on a great deal from the simple cell splitting ideas presented in [1]. A combination of intelligent small cells for indoor and hot spots and macrocells can provide the complete area coverage that can satisfy energy, coverage and capacity constraints that future cellular deployments will have to deal with. The remainder of this paper reviews current small cell technologies and then goes on to discuss the challenges that future small cells will face.

2. Small Cells Today

Today, femtocells have emerged as the first step towards a heterogeneous network deployment model. Femtocells are low cost cellular base stations, deployed by the end-user in the home in a plug-and-play manner, that use a broadband internet connection as backhaul [6].

The femtocell market is currently taking off with several network operators having already launched femtocell services and many others are currently running trials. For network operators, femtocells are a simple and cost effective way to significantly increase capacity and resolve coverage problems in indoor environments.

Today, femtocells are mainly marketed for coverage reasons and their capability of providing cheap high data rate services is largely neglected. However this is likely to change when smart phone usage makes internet access ubiquitous. One reason for this is voice which is still the predominant application. Therefore, most end users do not experience capacity problems as severely as coverage problems where no call is possible. Currently, femtocells are typically using the UMTS or CDMA air interface and are employing a private access model where only a limited group of registered mobiles can access the femtocell. In order to avoid interference with existing macrocellular networks, femtocells are usually deployed on a separate carrier.

The following challenges or limitations exist with most femtocell rollouts today:

- **Suboptimal spectrum utilization.** When femtocells are deployed on a separate carrier, this spectrum is not available for macrocells which limits their capacity. This will be an increasing problem when data services become more widely spread.

- **Interference in dense deployments.** The private access model used can result in significant interference in dense deployments such as apartment blocks where users can be located very close to a neighboring femtocell to which they do not have access to.

- **Mobility between macro- and femtocells.** As small cells become more widely deployed the increased mobility signaling becomes a problem. In residential femtocell deployments this is caused by cells providing coverage in areas outside of the home which trigger idle mode mobility events and handover attempts for passing users.

- **Energy consumption.** Increasing costs of energy and international focus on climate change issues have resulted in high interest in reducing the energy consumption of networks. While small cells have the potential to reduce the transmit power by a factor of 10^3 or more compared to macrocells, most femtocells are idle but still consuming power.

- **Typically limited to residential deployments.** Most femtocells deployed today are tailored to the residential market and are currently not well suited for enterprise or outdoor deployments because they typically do not support joint optimization of coverage, load balancing, and mobility between femtocells, as required for such scenarios.

In the following section we discuss these issues in more detail and highlight potential solutions and areas for research.

3. What About the Future?

As small cells become more mature the issues highlighted above will be addressed and more advanced solutions will become commercially available:

- **Improved spectrum efficiency through co-channel operation.** For future small cell deployments advanced optimization techniques can enable efficient co-channel operation. As a result no carrier needs to be reserved purely for small cells anymore. There are different options available for co-channel operation.

  In the case of full frequency re-use all macrocell carriers are also used for small cell transmissions, which provides the best spectral efficiency per area due to a high spatial frequency re-use factor.

However limitations of full re-use are that a public access model is required to prevent coverage holes for macrocell users in vicinity of small cells, and a significant increase in the number of resulting mobility events [7][8].
An alternative is partial frequency re-use where not all macrocell carriers are re-used by small cells [9]. While providing slightly less spectral efficiency this approach has no limitations regarding the access model and allows reducing the number of mobility events by scheduling mobile users to the clean macrocell carrier which prevents frequent handovers to small cells.

These concepts remain applicable when moving from UMTS or CDMA to OFDMA based air interfaces such as LTE, which allow a more fine-grained allocation of shared and clean frequency resources.

- **Interference mitigation techniques.** The requirement for co-channel operation and the increasing density of small cells results in interference which needs to be mitigated.
Power control is a simple method that can be used to mitigate interference. In [7] power self-optimization methods for downlink and uplink are presented that enable efficient co-channel operation of femtocells with macrocellular networks.

Interference can be further reduced by employing intelligent interference avoidance mechanisms. This however goes hand in hand with limiting the bandwidth per user, which results in a tradeoff between system capacity and cell edge performance. For UMTS or CDMA usually multiple carriers are required for interference avoidance. OFDMA based air interfaces such as LTE make interference avoidance easier due to the higher flexibility of resource allocation in time and frequency. One example of a distributed interference avoidance scheme for OFDMA is presented in [10]. In general, interference avoidance schemes benefit from more available spectrum and from allocation flexibility.

For residential femtocells, spectrum sharing between multiple operators would help to make more bandwidth available locally which can reduce interference issues by providing additional flexibility [11]. Another option for increasing the available spectrum is opportunistic spectrum access [12] where currently unused spectrum can be re-used locally. In essence these approaches are elements of cognitive radio techniques being applied to small cell scenarios.
Additional promising approaches for interference mitigation are using intelligent antenna techniques[13], or interference cancellation.

- **Minimizing and improving mobility procedures.** The potentially significant increase in core network signaling resulting from mobility events need to be addressed. For residential femtocells this can for example be minimized by coverage optimization [14].

Furthermore, when using a partial frequency re-use scheme as describe above, intelligent handover mechanisms that move users with high mobility or low bandwidth requirements to clean macrocell carriers and static users to small cells can reduce the increase of such mobility events.

In addition to efforts aiming at reducing the number of mobility events, flat network architectures have been proposed to make mobility procedures more efficient [15]. However, more research in these areas is required to cope with future small cell deployments particularly in public spaces.

- **Improved energy efficiency through idle modes.** An “energy follows load” principle will be required for future small cell deployments. Idle mode procedures have been proposed for residential femtocells [16] which allow most of the functions being switched on only for the duration of serving a call which significantly reduces the energy consumption of femtocells. Moreover, it is expected that in addition, idle mode procedures will also result in further benefits such as reduced power density in the home, mobility procedures, and pilot interference. Some of the items mentioned here will form the basis for outdoor and enterprise small cell solutions, however more research is required to identify optimal solutions in this area.

To realize the full benefit of idle mode control, a modular hardware design is required that allows to quickly enable and disable all components such that the energy consumption becomes proportional to the load. Furthermore, changes to the link protocols may be required to keep the link state without communication in idle modes.
In the longer term, new location update procedures that do not rely on continuous pilot transmissions can result in further energy savings.

- **Scenario flexibility.** While today femtocells only serve the residential market this will change in the near future as the solutions to the challenges described here mature to include also enterprise and street level outdoor deployments. A further option are publicly accessible residential small cell deployments which have a high potential for overall network cost and energy savings [17][18].

  These deployments require fundamentally different auto-configuration and self-optimization approaches since the objectives are different compared to today's residential femtocells.

  One example is the coverage optimization in an enterprise environment [19] where multiple cells must now work together to jointly minimize coverage holes, balance load and minimize unnecessary outdoor coverage.

Overall, small cell networks will become more intelligent and cognitive as more generic deployment solutions are sought. One driver for this is the key requirement of self-optimization capability for small cells which needs to work well for diverse and changing environments and user demand. Static self-optimization algorithms are sometimes limited in their applicability when the assumptions under which they were designed change. Recent research has focused on applying machine learning approaches such as genetic programming or reinforcement learning to address this problem. For example in [20] genetic programming is used to automatically evolve a distributed coverage self-optimization algorithm. Another example is [21] where teaching of already learned information is proposed to improve convergence time of the learning process.

Finally, as the technology of small cells becomes mature it will impact adjacent technology areas primarily because of the topological changes in the network. Eventually cost constraints in the network will mean that network virtualization and infrastructure sharing will have to be incorporated into small cell networks. From an application perspective, because of the higher localization of the end user (smaller cell size and fewer numbers of users per cell) could influence where data and applications are stored, for some applications it may be more beneficial to buffer data close by.

Conclusions

This paper provided an overview about the future of small cells networks. Problems of existing small cell solutions were highlighted and different approaches of how they can be addressed in the future were discussed. This includes improving spectrum efficiency, dealing with interference issues, minimizing mobility procedures and associated signaling, improving energy consumption, and required changes to make small cells more generally applicable in enterprise and outdoor deployments. Within these areas examples of existing work were given and opportunities for further research highlighted. In addition broader trends in telecommunications were discussed that are relevant for small cells such as making networks more intelligent, network virtualization to drive down costs, application based networking and local storage of relevant information.

References

[1] A. C. Stocker, "Small-cell mobile phone systems," *IEEE Transactions on Vehicular Technology,* vol. 33,
is. 4 pp. 269 – 275, 1984.

[2] R. Iyer, J. Parker and P. Sood, "Intelligent networking for digital cellular systems and the wireless world" in *Proc of Global Telecommunications Conference (GLOBECOM),* vol. 1, pp: 475 – 479, *1990*.

[3] L. T. W. HO "Self-organising algorithms for fourth generation wireless networks and its analysis using complexity metrics", *PhD Thesis, Queen Mary College, University of London, June 2003.*

[4] H. Claussen, L. T. W. Ho, H. R. Karimi, F. J. Mullany, L. G. Samuel, "I, base station: Cognisant robots and future wireless access networks" in *Proc. 3rd IEEE Consumer Communications and Networking Conference (CCNC)*. vol 1, pp 595 – 599, *2006*.

[5] D. C. Kilper, *et al*, "Power trends in communication networks" to appear in IEEE Journal of Special Topics in Quantum Electronics.

[6] H. Claussen, L. T. W. Ho, and L. G. Samuel, "An overview of the femtocell concept," *Bell Labs Technical Journal*, vol. 13, no. 1, pp. 221-245, May 2008.

[7] H. Claussen, "Co-channel operation of macro- and femtocells in a hierarchical cell structure," *International Journal of Wireless Information Networks*, vol. 15, no. 3, pp. 137-147, Dec. 2008.

[8] L. T. W. Ho and H. Claussen, "Effects of user-deployed, co-channel femtocells on the call drop probability in a residential scenario," in *Proc. 18th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Athens, Greece, Sept. 2007.

[9] J. D. Hobby and H. Claussen, "Deployment options for femtocells and their impact on existing

macrocellular networks," *Bell Labs Technical Journal*, vol. 13, no. 4, pp. 145-160, Feb. 2009.

[10] A. L. Stolyar, H. Viswanathan, "Self-organizing dynamic fractional frequency reuse in OFDMA systems," in *Proc. 27th IEEE Conference on Computer Communications INFOCOMM*, pp. 691-688, 2008.

[11] Digital Communications Knowledge Transfer Network "Small cell networks," Position paper, January 2010, https://ktn.innovateuk.org/c/document_library/get_file?p_l_id=737699&folderId=865485&name=DLFE-7020.pdf

[12] M. M. Buddhikot, I. O. Kennedy, F. J. Mullany, H. Viswanathan "Ultra-broadband femtocells via opportunistic reuse of multi-operator and multi-service spectrum," *Bell Labs Technical Journal*, vol. 13, no. 4, pp. 129-143, 2009.

[13] A. M. Kuzminskiy, Y. I. Abramovich, "Decentralized Dynamic Spectrum Allocation Based on Adaptive Antenna Array Interference Mitigation Diversity," IEEE Trans. Sig. Proc., vol. 58, no. 4, Apr. 2010.

[14] H. Claussen, L. T. W. Ho, and F. Pivit, "Self-optimization of femtocell coverage to minimize the increase in core network mobility signalling," *Bell Labs Technical Journal*, vol. 14, no. 2, pp. 155-184, Aug. 2009.

[15] M. Bauer, P. Bosch, N. Khrais, L. G. Samuel, P. Schefczik, "The UMTS base station router," Bell *Labs Tech. Journal*, vol. 11, no. 4, pp. 93–111, 2007.

[16] I. Ashraf, L. T. W. Ho, and H. Claussen, "Improving energy efficiency of femtocell base stations via user activity detection," *in Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Sydney, Australia, Apr. 2010.

[17] H. Claussen, L. T. W. Ho, and L. G. Samuel, "Financial analysis of a pico-cellular home network deployment," in *Proc. IEEE International Conference on Communications (ICC)*, Glasgow, UK, pp. 5604-5609, June 2007.

[18] H. Claussen, L. T. W. Ho, and F. Pivit, "Leveraging advances in mobile broad-band technology to improve environmental sustainability," *Telecommunications Journal of Australia*, vol. 59, no. 1, pp. 4.1-4.18, Feb. 2009.

[19] I. Ashraf, H. Claussen, L. T. W. Ho, "Distributed radio coverage optimization in enterprise femtocell networks," in *Proc. IEEE International Conference on Communications (ICC)*, 2010.

[20] L. T. W. Ho, I. Ashraf, and H. Claussen, "Evolving femtocell coverage optimization algorithms using genetic programming," in *Proc. 20th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Tokyo, Japan, Sept. 2009.

[21] L. Giupponi, A. Galindo-Serrano, P. Blasco, M. Dohler, "Docitive networks: an emerging paradigm for dynamic spectrum management," *IEEE Wireless Communications*, vol. 17, is. 4, pp. 47-54, 2010.

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TECHNOLOGY ADVANCES

Multimedia Communication in Wireless Networks

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Mobile computers, such as PDAs and laptop computers with multiple network interfaces are becoming very common. Many of the applications that run on a mobile computer involve multimedia, such as video conferencing, audio conferencing, watching live movies, sports, etc. In fact, multimedia transmissions are booming over a variety of wireless networks, and are becoming a more critical and attractive application in mobile and embedded devices. Given the importance of wireless multimedia communication, a special issue is solely dedicated to multimedia communication in mobile wireless networks. Extensive research has been carried out to ensure a smooth and uninterrupted multimedia transmission from mobile devices over wireless media. I have thus assembled seven position papers from leading personalities, who span five different countries in this research area, and have various backgrounds.

First, "*Separation Principles for Multimedia Delivery over Energy Efficient Networks*" from Fangwen Fu and Mihaela van der Schaar develops a unified framework for transmitting delay-sensitive multimedia traffic data over wireless networks. Second, in "*Cooperative Video Multicast using Randomized Distributed Space Time Coding*", Ozgu Alay, Yao Wang, Elza Erkip and Shivendra S. Panwar propose a cooperative layered video multicasting scheme using R-DSTC, along with packet level FEC, to enable error resilient video delivery. Third, "*HAPS Ad Hoc Networks: Key Theory and Technology*" written by Xinbo Gao and Ru Zong discusses some major technological challenges of high altitude platform stations (HAPS) in ad hoc networks. Fourth, "*Analysis of Delay in Cognitive MAC for Mobile Multimedia Communications*" co-authored by Tao Jiang, Zhiqiang Wang, Liang Yu and Peng Gao, investigates the delay when two nodes successfully access the idle licensed channel in cognitive radio networks. Fifth, "*Reducing the Channel Switching Delay in IP-based Multi-channel Streaming*" contributed by Toshiaki Ako, Hiroki Nishiyama, Nirwan Ansari, Nei Kato discusses several existing approaches to reduce the channel switching delay based on IP multicast and Application Layer Multicast. Sixth, in "*Multimedia over Sensor Networks*", Lei Shu and Min Chen introduce the concept of Mobile Multimedia Sensor Networks and present a few research challenging issues. Finally, "*LEM: a Cooperative and Self-Organizing Flow Relaying Middleware for Multimedia Continuity in Dense Hybrid Wireless Networks*" by Paolo Bellavista, Antonio Corradi, Luca Foschini demonstrates the suitability of dynamic mobile relay collaboration for seamless multimedia streaming in hybrid wireless networks with dense AOIs.

I hope you will enjoy reading these contributions of this special issue dedicated to multimedia communication in wireless networks.

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September 2010

Weiyi Zhang is an Assistant Professor at Computer Science Department, North Dakota State University. Before joining NDSU, he earned my Ph.D. degree from the Department of Computer Science and Engineering, Arizona State University. He has more than 50 refereed papers published/accepted in my research areas, including papers in prestigious conferences and journals such as IEEE INFOCOM, ACM MobiHoc, IEEE/ACM Transactions on Networking, ACM Wireless Networks, IEEE Transactions on Vehicular Technology and IEEE Journal on Selected Areas in Communications. He has been serving as a reviewer or a technical committee chair/member for many internationally reputable journals and conferences, such as IEEE/ACM Transactions on Networking, IEEE Transactions on Mobile Computing, IEEE Transactions on Wireless Communications, IEEE/OSA Journal of Optical Communications and Networking, Elsevier Journal of Computer Networks, IEEE INFOCOM, IEEE GLOBECOM and IEEE ICC.

Separation Principles for Multimedia Delivery over Energy Efficient Networks

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1. Introduction

Delay-sensitive communications (e.g. multimedia transmission) are booming over a variety of wireless networks. However, the concepts and methods that have dominated multi-user communication and networking research in recent years are not well suited for efficiently designing and implementing systems aimed at supporting delay-sensitive applications, because they often ignore one or more of the following key challenges: (i) the *time-varying, and error-prone* network environment; (ii) the *energy constraints* of the involved network entities; (iii) the *time-varying and heterogeneous* traffic requirements of the supported multimedia applications (e.g. heterogeneous delay deadlines, distortion impacts, and dependencies among data packets); and (iv) the inherent *decentralization of information and control* among the interconnected network entities.

In the literature, the problem of energy-efficient scheduling and transmission over wireless channels has been intensively investigated in [4]-[8]. However, existing solutions often do not consider key properties of delay-critical applications [4]-[7] such as packet interdependencies (e.g. due to compression or joint processing), their heterogeneous delay deadlines, and their different priorities, or disregard the time-varying characteristics and energy constraints of the considered transmission network [8]. Another strand of work is based on stability-constrained optimization methods [9][10], where instead of minimizing the delay experienced by the traffic data, queue stability is imposed. The optimal energy consumption is achieved only for asymptotically large queue sizes (corresponding to asymptotically high delay). Consequently, stability constrained methods do not provide optimal energy consumption when the applications have low (hard) delay requirements.

Another key limitation of most existing solutions for designing and configuring wireless systems assume that statistical knowledge of the underlying dynamics (e.g. channel state distribution, packet arrival distribution, etc.) is known [4]. When this knowledge is not available, only heuristic solutions are provided, which cannot guarantee optimal performance because they do not learn to make foresighted decisions based on the experienced dynamics. Alternative methods for optimizing transmission in unknown environments rely on online learning algorithms based on reinforcement learning [11]. However, these methods often incur large memory overheads for storing the state-value function and they are slow to adapt to new or dynamically changing environments.

When multiple wireless systems operate in the same resource-constrained wireless network infrastructure, it is needed to efficiently coordinate with each other to share the limited network resources. Numerous state-of-the-art resource allocation and coordination techniques are based on the network utility maximization (NUM) framework [12]. In the NUM framework, the basic assumption is that each user has a *static utility function* of the (average) allocated transmission rate (or Quality-of-Service), which is often not true in delay-sensitive multimedia transmission scenarios.

In summary, to support the delay-sensitive multimedia applications, a new foundation for systematically designing and optimizing multi-user networks and distributed systems is necessary, where it is possible for systems to autonomously (i) minimize the experienced delay under energy constraints; (ii) learn to operate optimally in time-varying and a priori unknown environments by deploying low-complexity online learning algorithms; and (iii) coordinate with each other in an informationally-decentralized manner in order to optimally utilize the available network resources and maximize the overall network performance.

In this contribution, we briefly summarize the main principles and concepts behind a unified foresighted optimization framework developed by us in [1]-[3], which is able to address the abovementioned challenges in order to optimize the long-term utility of delay-sensitive applications. Although our framework can be applied to both wireless and wired networks, our focus in this contribution is transmission over wireless networks.

Our proposed unified framework relies on three separation principles (which are depicted in Fig. 1), which are theoretically important for designing delay-sensitive communication systems. First, by introducing the post-decision states, we separate the foresighted decisions from the underlying network dynamics, which enables us to explore the structures of the optimal solutions and design low-complexity algorithms. Second, in order to explicitly consider the heterogeneity of the multimedia traffic, we prioritize the delay-sensitive data (expressed as direct acyclic graphs) and separate the multi-data unit foresighted decision into multiple single-data unit foresighted decisions, which can subsequently be performed from the high priority to the low priority. Third, when multiple delay-sensitive applications coexist in the wireless network, by introducing a resource price and relaxing the network resource constraints imposed on the future transmission, we separate the multi-user foresighted decision into multiple single-user foresighted decision, thereby significantly reducing the computation and communication complexity.

Implementing the above framework in practice requires statistical knowledge of the network dynamics, which is often unavailable before transmission time. To overcome this obstacle, we propose novel structure-aware online learning algorithms derived from the above three separation principles. The proposed online learning algorithms have low complexity and fast convergence, and achieve ε-optimal solutions, which can significantly improve the delay-sensitive communication performance in the unknown environments.

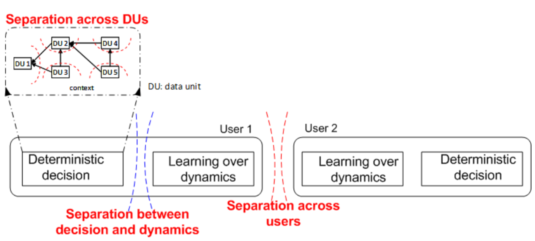

Fig. 1. Three separation principles for multimedia networks.

2. Separation between decision and dynamics

In this section, we demonstrate how to separate the decision on transmission strategies from the underlying dynamics, and how to unravel the *structural properties* of the optimal solutions, which we exploit to simplify their implementation. We focus on the problem of energy efficient point-to-point (i.e. a transmitter-receiver pair, which is referred to here as a wireless user) transmission of (average) delay-sensitive traffic over a time-varying wireless channel. This serves as the basic model for the heterogeneous data. More details in modeling the heterogeneous data are discussed in Section 3 and in [3]. We assume that the transmission is time-slotted and we model it as in Fig. 2.

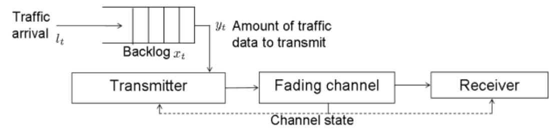

Fig. 2. Wireless user transmission model.

Similar to [4], we formulate this problem as a foresighted optimization by using a Markov decision process (MDP) which is aimed to optimize the trade-off between the long-term utility and long-term transmission cost (e.g. energy) and is given by:

$$\max_{y_t \geq 0, \forall t} E\left[\sum_{t=0}^{\infty} \alpha^t \left(u(x_t, y_t) - \lambda c(h_t, y_t)\right)\right] \quad (1)$$

where x_t , h_t and y_t denotes the backlog, the channel condition and the amount of data determined to be transmitted (i.e. the scheduling action) at the beginning of time slot $t \in \mathbb{Z}_+$, $u(x_t, y_t)$ and $c(h_t, y_t)$ are the utility and cost when transmitting the amount y_t of data, and $\alpha \in [0, 1)$ is the discount factor and $\lambda \geq 0$ is the trade-off parameter. In Eq. (1), the long-term utility (transmission cost) is defined as the discounted sum of utility and transmission cost trade-off. When $\alpha \to 1$, (1) is equivalent to optimizing the trade-off between the average utility and transmission cost [4].

In the conventional solutions to problem (1), the expectation over the channel states and packet arrivals must be performed before the maximization over the scheduling actions at each time slot. Hence, performing the maximization requires knowledge of the channel dynamics, which makes the system design more complicated. In contrast, we introduce an intermediate state that represents the state after scheduling the data but before the new data arrives and new channel state is realized. This intermediate state is referred to as the *post-decision state* $\tilde{s} = (\tilde{x}, \tilde{h})$ and the value function over the post-decision states is referred to as the *post-decision state-value function (SVF)* V which represents the optimal value starting from the post-decision state. The relationship between the post-decision state $\tilde{s}_t = (\tilde{x}_t, \tilde{h}_t)$ and the conventional state $s_t = (x_t, h_t)$ is illustrated in Fig. 3.

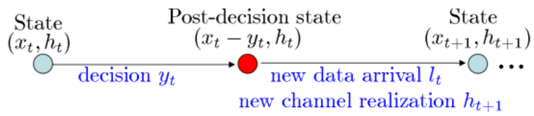

Fig. 3. Illustration of post-decision state.

The post-decision SVF V satisfies the following Bellman equations:

$$V^*(x,h) = E_{l,h'|h} J^*(x+l,h') \quad (2)$$

$$J^*(x,h) = \max_{y\in[0,x]} [u(x,y) - \lambda c(h,y) + \alpha V^*(x-y,h)] \quad (3)$$

The first equation shows that the post-decision SVF V^* is obtained from the conventional SVF J^* by taking the expectation over the possible traffic arrivals and channel transitions. The second equation shows that the conventional SVF can be obtained from the post-decision SVF V^* by performing the maximization over the possible scheduling actions. We notice that the decision on the amount of data to transmit (corresponding to Eq. (3)) is separated from the expectation over the underlying dynamics (corresponding to Eq. (2)).

Under the mild assumptions (convexity and supermodularity) on the utility $u(x,y)$ and $c(h,y)$ [2], we can show that the post-decision SVF $V^*(x,h)$ is a concave function in x and that the optimal scheduling policy $\pi^*(x,h)$ is non-decreasing in x for any given h. Any concave function can be approximated using a piece-wise linear function. Due to the concavity of the post-decision SVF, we are able to trade off the computational complexity for computing the optimal post-decision SVF and the performance of the corresponding optimal policy by using a predetermined approximation error threshold λ. We notice that, starting with any piece-wise linear concave function V_0, value iteration using the dynamic programming operator [13] with adaptive approximation converges to an e-optimal post-decision SVF V^*, where $\varepsilon = 1/(1-\alpha)$. Thus, to guarantee an e-optimal solution, we can choose $\delta = \varepsilon(1-\alpha)$. When the statistical knowledge of the dynamics is unknown a-priori, we develop an online-learning algorithm which updates the post-decision SVF using batch update methods and adaptive piece-wise linear approximation. More details can be founded in [2].

We notice that, instead of minimizing the trade-off between the delay and the energy consumption, the stability-constrained optimization minimizes the trade-off between the Lyapunov drift (between the current state and post-decision state) and energy consumption, which is a special case of our proposed framework and achieves suboptimal delay-energy trade-off (see Fig. 4). We also notice that, instead of updating the post-decision state-value function, the Q-learning algorithm updates the state-action value function only at the visited state-action pair per time slot, which has significantly slow learning rate and is not suitable for our delay-sensitive application.

Fig. 4. shows the delay-energy consumption trade-offs, from which it is clear that our proposed method outperforms the stability constrained optimization at both the high delay region (≥150 ms) and the low delay region. In the low delay region, the proposed method can reduce the delay by 70% or more, which is very important for the delay-sensitive applications.

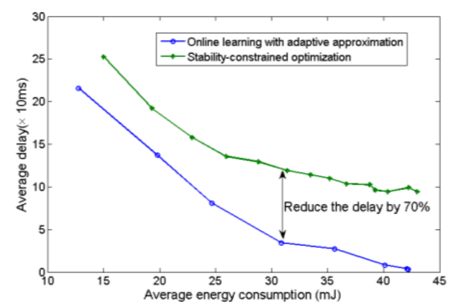

Fig. 4. Delay-energy trade-off under various channel conditions.

3. Separation Across DUs

The multimedia data is often encoded periodically using a Group of Pictures (GOP) structure. The multimedia data within one GOP are encoded interdependently using, e.g. motion estimation, while the data belonging to different GOPs are encoded independently. Note that the prediction-based coding schemes often lead to sophisticated dependencies. After being encoded, each GOP contains multiple data units (DUs), each representing one type of DU (e.g. I, P, B frames in encoded video bitstream). To capture the heterogeneous characteristics of DUs, we first introduce the concept of a “context” at each time slot to represent the heterogeneity of the DUs available for transmission at each time slot. It is worth to know that, the context indicates the distortion impacts of the DUs and the dependencies between DUs and the context transition indicates the delay deadlines of the DUs.

Through the context concept, we are able to capture the dynamic features of the multimedia packets across time. We then formulate the dynamic packet scheduling optimization as a Markov decision process (MDP) problem by further considering the underlying channel dynamics. Within the MDP formulation, the packet scheduling is performed in a foresighted fashion in order to maximize the long-term reconstructed multimedia quality.

In order to reduce the complexity involved in computing the packet scheduling policy, we define the transmission priorities of the DUs in each context based on the distortion impacts, delay deadlines and dependencies, and express them as a DAG, which we refer to simply as the priority graph. Different from the DAG expression on the source coding dependencies in [8], the proposed DAG construction represents the transmission priorities which include the packet dependencies. Through the priority graph, we are able to *separate* the multi-DU foresighted decision at each time slot into multiple single-DU foresighted decisions and the two-phase packet scheduling is applied to each individual DU, which significantly reduce the complexity in computing the optimal foresighted decisions.

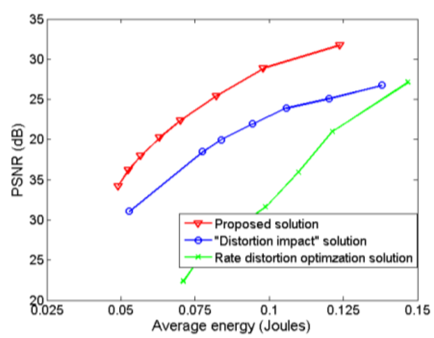

Fig. 5. PSNR-energy curve of Foreman video sequence using different transmission solutions

In the unknown environment, we further develop an online learning algorithm to estimate the post-decision state value functions. Based on the separation developed for multi-DU foresighted optimization, we are able to estimate the post-decision state value functions for each DU using a low-complexity online learning method.

We consider three comparable solutions: (i) our proposed packet scheduling solution; (ii) “distortion-impact” driven packet scheduling [6][7] which only considers the distortion impact of each media packet and the observed channel conditions; (iii) the rate-distortion optimized packet scheduling as in RaDiO [8]. From Fig. 5, we note that our proposed optimization solution outperforms both the ”distortion-impact” driven packet scheduling and rate-distortion optimized packet scheduling by, on average, around 2dB and 5dB in terms of PSNR. The improvement comes from the fact that our proposed solution schedules the packets based on the heterogeneous characteristics of the multimedia packets as well as the time-varying channel conditions.

4. Separation across users

In this section, we show how to establish a formal and systematic framework for coordinating wireless users when multiple wireless users share the same wireless network resource. Importantly, the proposed framework provides the necessary foundations and principles for how the wireless users can autonomously learn on-line to cooperatively optimize the performance of the whole wireless network when the dynamics are unknown. For simplicity, we consider the problem of resource allocation and scheduling in a multi-user single-hop wireless network.

By extending the formulation of single-user multimedia transmission presented in Section 3, we formulate the optimization for coordinating the wireless users to share the network resources in the dynamically changing environment as a weakly-coupled multi-user MDP (MUMDP) problem. The MUMDP formulation allows each wireless user to make foresighted transmission decisions by taking into account the impact of its current decisions on the long-term utilities of all the wireless users.

Unlike centralized solutions to the MDP, which have very high computation complexity and communication overheads that lead to unacceptable delays for delay-sensitive multimedia applications, we propose to use Lagrangian relaxation to decompose this weakly-coupled MUMDP problem into multiple local MDPs, each of which can be separately solved by the individual wireless users. This decomposition is different from the conventional dual solutions [12] to the multi-user NUM-based video transmission problem in two ways: (i) instead of maximizing the static utility at each transmission time, our approach allows each wireless user to solve the dynamic optimization problem (formulated as a local MDP), which is vital for the delay-sensitive wireless user; (ii) instead of updating the Lagrangian multipliers only based on the current resource requirements of the wireless users, our approach also updates the multipliers depending on the their future predicted resource needs, such that the long-term utility of all the wireless users is maximized (thereby maximizing the long-term global utility of the wireless network). To the best of our knowledge, this is the first attempt to formalize the dynamic interaction between autonomous, yet collaborative, wireless users with the goal of allowing them to maximize the long-term global utility of a wireless network in a distributed manner.

The preliminary results on achieved video qualities of three wireless users (User 1 streams “Foreman” video sequence, User 2 streams “Coastguard” sequence and User 3 streams “Mobile” sequence) are presented in Table 1. Compared to the repeated NUM [6][12], our algorithms can improve the video quality by around 1.5 dB on average for all the wireless users.

Table 1. Video quality (in dB) for three users

	User 1	User 2	User 3
Proposed solution	33.5	30.4	26.3
Repeated NUM [12]	32.8	28.6	24.4

5. Conclusion

We develop a unified framework for transmitting delay-sensitive multimedia traffic data over wireless networks. This proposed framework can (i) explicitly consider the heterogeneous characteristics of the delay-sensitive multimedia traffic data; (ii) explore and exploit the structural properties of the optimal solutions; (iii) efficiently utilize the limited battery energy of (mobile) devices; (iv) provide a low-complexity online learning algorithm that preserves the structural properties and achieves ε-optimal solutions in a priori unknown environments; and (v) provide a distributed coordination mechanism that enables the users to autonomously solve their own local dynamic optimizations based on not only current, but also the future resource needs of all users, such that the long-term utilities of all users is maximized. This framework has been extended to multi-hop wireless networks [14], peer-to-peer networks [15], energy-efficient dynamic multimedia processing systems [16] and layered, multi-view or reconfigurable codecs [17].

References

[1] F. Fu and M. van der Schaar, "A Systematic Framework for Dynamically Optimizing Multi-User Video Transmission," IEEE J. Sel. Areas Commun., vol. 28, no. 3, pp. 308-320, Apr. 2010.

[2] F. Fu, and M. van der Schaar, “Structure-Aware Stochastic Control for Transmission Scheduling,” Technical Report, 2010. [online: www.arxiv.org/pdf/1003.2471]

[3] F. Fu, and M. van der Schaar, “Structural Solutions to Dynamic Scheduling for Multimedia Transmission in Unknown Wireless Environments,” Technical Report, 2010, [online: http://medianetlab.ee.ucla.edu/publications.html]

[4] R. Berry and R. G. Gallager, “Communications over fading channels with delay constraints,” IEEE Trans. Inf. Theory, vol 48, no. 5, pp. 1135-1149, May 2002.

[5] J. Huang, Z. Li, M. Chiang, and A.K. Katsaggelos, “Joint Source Adaptation and Resource Allocation for Multi-User Wireless Video Streaming,” IEEE Trans. Circuits and Systems for Video Technology, vol. 18, issue 5, 582-595, May 2008.

[6] E. Maani, P. Pahalawatta, R. Berry, T.N. Pappas, and A.K. Katsaggelos, “Resource Allocation for Downlink Multiuser Video Transmission over Wireless Lossy Networks,” IEEE Transactions on Image Processing, vol. 17, issue 9, 1663-1671, September 2008.

[7] M. van der Schaar, and S. Shankar, “Cross-layer wireless multimedia transmission: challenges, principles, and new paradigms,” IEEE Wireless Commun. Mag., vol. 12, no. 4, Aug. 2005.

[8] P. Chou, and Z. Miao, “Rate-distortion optimized streaming of packetized media,” IEEE Trans. Multimedia, vol. 8, no. 2, pp. 390-404, 2005.

[9] L. Tassiulas and A. Ephremides, “Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks,” IEEE Transacations on Automatic Control, vol. 37, no. 12, pp. 1936-1949, Dec. 1992.

[10] L. Georgiadis, M. J. Neely, and L. Tassiulas, “Resource allocation and cross-layer control in wireless networks,” Foundations and Trends in Networking, vol. 1, no. 1, pp. 1-149, 2006.

[11] N. Salodkar, A. Bhorkar, A. Karandikar, and V. S. Borkar, “An on-line learning algorithm for energy efficient delay constrained scheduling over a fading channel,” IEEE Journal on Selected Areas in Communications 26(4): 732-742, 2008.

[12] M. Chiang, S. H. Low, A. R. Caldbank, and J. C. Doyle, “Layering as optimization decomposition: A mathematical theory of network architectures,” Proceedings of IEEE, vol. 95, no. 1, 2007.

[13] D. P. Bertsekas, “Dynamic programming and optimal control,” 3rd, Athena Scientific, Massachusetts, 2005.

[14] H. P. Shiang and M. van der Schaar, "Online Learning in Autonomic Multi-Hop Wireless Networks for Transmitting Mission-Critical Applications," IEEE J. Sel. Areas Commun., vol. 28, no. 5, pp. 728-741, June 2010.

[15] H. Park and M. van der Schaar, "Evolution of Resource Reciprocation Strategies in P2P Networks", IEEE Trans. Signal Process., vol. 58, no. 3, pp. 1205-1218, Mar. 2010.

[16] N. Mastronarde and M. van der Schaar, "Online Reinforcement Learning for Dynamic Multimedia

Systems," IEEE Trans. on Image Processing, vol. 19, no. 2, pp. 290-305, Feb. 2010.

[17] N. Mastronarde and M. van der Schaar, "Designing Autonomous Layered Video Coders," Elsevier Journal Signal Processing: Image Communication - Special Issue on *Scalable coded media beyond compression*, vol. 24, no. 6, pp. 417-436, July 2009.

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Cooperative Video Multicast using Randomized Distributed Space Time Coding

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1. Introduction

With the increased popularity of mobile multimedia services, efficient and robust video multicast strategies are of critical importance. However, wireless video multicast is a challenging problem due to variations in channel qualities between the source and each receiver.

Cooperative communications, where terminals process and forward the overheard signal transmitted by other nodes to their intended destination [1], is an effective technique to combat channel variations that arise from fading. User cooperation is suitable for multicast not only because of its ability to substantially reduce the packet losses, but also because the relays are part of the multicast group.

In cooperative networks, there may be more than one node that can overhear the packet sent by the source, and using a distributed space-time code (DSTC) [2], the nodes can relay simultaneously in a spectrally efficient way. The basic idea behind DSTC is to coordinate and synchronize the relays such that each relay acts as one antenna of a regular Space Time Code (STC). However, DSTC requires tight coordination among the source and relays, leading to significant overhead at the MAC layer. Furthermore, DSTC works with a fixed number of relays and cannot exploit other nodes that receive the source information.

Randomized DSTC (R-DSTC) [3] circumvents some of these problems by having each relay transmit a random linear combination of antenna waveforms. R-DSTC not only loosens the coordination, but also enables a variable number of relays. R-DSTC is especially attractive for multicast since the nodes that receive the packets can act as relays and transmit simultaneously, hence there is no need for relay selection and scheduling.

In this paper, we study video multicast using R-DSTC (*multicast-RDSTC*) in infrastructure-based networks such as Wi-Fi and cell-phone networks. In order to handle packet losses, we further employ packet level Forward Error Correction (FEC). We discuss the selection of transmission rates of the first and second hops, the STC dimension and FEC rate to maximize the supportable video rate at all nodes. We evaluate the performance of the proposed system and compare with conventional multicast and rate adaptive direct transmission.

2. Preliminaries

Packet level FEC is a promising solution for error control in video multicast over wireless networks. The basic idea of FEC is that redundant information is sent a priori by the source, in order to be used by the receivers to correct errors/losses without contacting the source. The advantage of using packet level FEC for multicasting is that any parity packet can be used to correct independent single-packet losses among different nodes. With packet level FEC, for every **k** source packets, we need to send **m** parity packets if we anticipate at most **m** lost packets in every **k**+**m** transmitted packets, in order to recover all the source packets. The resulting FEC rate is $\gamma = k/(k+m)$. In our study, **k** is fixed, and for a given maximum packet loss rate (PER), ε_{max}, we choose **m** and hence γ so that the FEC decoding failure probability is negligible. Thus γ is a function of ε_{max}, and we assume all video packets can be recovered successfully with this choice of γ.

With conventional multicast (to be called *Direct*) we assume that when the transmission rate is R_d, the maximum PER among all users in the coverage area of radius $\mathbf{r_d}$ is ε_{max} and the corresponding required FEC rate for direct transmission is $\gamma_d(\varepsilon_{max})$. Note that ε_{max} depends on R_d, and hence γ_d also depends on R_d and can generally be expressed as $\gamma_d(R_d)$. Therefore, the achievable video rate with direct transmission with transmission rate R_d is:

$$R_{vd} = \gamma_d(\mathrm{R_d})R_d$$

Note that as R_d increases, γ_d decreases, and there is an optimal R_d at which the video rate is maximized. Therefore, unlike conventional multicast, which always uses the lowest transmission rate, one can adapt the transmission rate based on the channel condition. This is referred to as *Direct-adaptive*.

3. Problem Formulation and Optimization for multicast-RDSTC

For the cooperative scheme, we assume that a video is divided into segments of duration **T** seconds., and the sender and the relays transmit over t_1 and t_2 fractions of each time interval **T** respectively, where $t_1+t_2=1$.

We assume the relays forward all the packets they receive without differentiating between the source and parity packets, hence the FEC rate, $\gamma_c(\varepsilon_{max})$ depends on the maximum PER among all users after two hop transmission, ε_{max}. Note that for cooperative transmission, ε_{max} not only depends on the first and second hop transmission rates but also the STC dimension, $\varepsilon_{max}(R_1, R_2, L)$. We compute the average PER experienced by each node in the multicast group using the formulation in [4]. We then find the maximum average PER among all users and hence the necessary FEC rate, which is also a function of R_1, R_2, L, and will be denoted as γ_c (R_1, R_2, L). Then, the video rates at Hop-1 and Hop-2 nodes are:

$$R_{v1} = \gamma_c(\mathrm{R}_1, \mathrm{R}_2, \mathrm{L}) R_1 t_1,$$
$$R_{v2} = \gamma_c(\mathrm{R}_1, \mathrm{R}_2, \mathrm{L}) R_2 t_2.$$

We choose t_1 so that Hop-1 and Hop-2 nodes receive the video at the same rate, i.e., $R_{vc} = R_{v1} = R_{v2}$. This yields $t_1 = R_2/(R_1 + R_2)$, and the corresponding video rate is:

$$R_{vc} = \gamma_c(\mathrm{R}_1, \mathrm{R}_2, \mathrm{L}) R_1 R_2/(R_1 + R_2)$$

We choose R_1, R_2, and L to maximize the supportable video rate. Note that we only consider orthogonal STC codes with L=2, 4, 8. For these STC dimensions, there exist real orthogonal designs that provide full rate for square constellations [5]. **L** is chosen as close as possible to the average number of relays $\mathbf{N_{avg}}$. Note that, for a large number of nodes, $\mathbf{N_{avg}}$ may be much larger than **L**.

4. Simulation Results

We study an IEEE 802.11g network and consider a coverage range of 100m radius, i.e. r_d=100m, where the source is at the center of the network and nodes are randomly uniformly located in this coverage range.

In our simulations, we consider different numbers of nodes corresponding to different density networks, and for each node density we generate 200 different node placements. We choose the transmission power of the source at the base rate, R_d=6 Mbps, such that all nodes in the coverage range experience an average PER of 5%, which is a practical assumption for multicast in wireless networks.

In order to have comparable energy consumption with direct transmission, we assume that the relay energy per symbol is set to $E_r = E_s / N_{avg}$ where E_s is the symbol energy of the source.

For the FEC computations, we use **k**=128 and choose **m** such that the FEC decoding failure probability is at most 0.5%. We observe that when using an error-resilient video decoder, there is no observable quality degradation when the failure rate is equal or below this threshold.

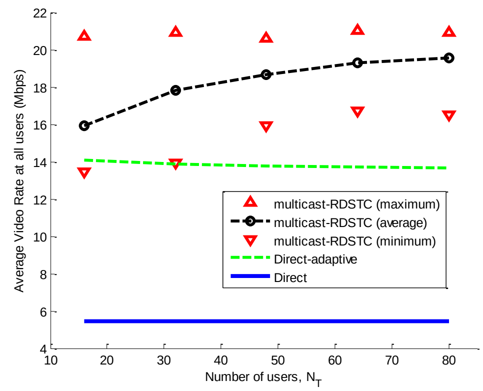

Fig. 1. Supportable video rates vs. number of nodes.

For direct transmission, we use the base transmission rate R_d=6 Mbps, and since we assume an average PER of 5% in the coverage range, we apply a FEC rate of γ_d =0.905.

In Figure 1, we illustrate the performance of different schemes as a function of the number of nodes in the network. As illustrated in the figure, for direct transmission, the video rate does not change with the number of nodes as transmission and FEC rates are fixed. For rate adaptive multicast, since the transmission and FEC rates are chosen based on the channel conditions, as the number of nodes increases, there is a higher chance that there will be some node at the edge of the coverage range, forcing the system to choose a lower FEC rate, thus yielding a lower video rate. For the cooperative multicast systems, we present the “maximum”, “minimum” and “average” video rates among all node placements to show the variation of the system due to different node placements. For multicast-RDSTC, as the number of nodes increases, more relays participate in the second hop transmission, making the end-to-end PER lower, and hence the supportable video rate higher. The performance of the proposed scheme outperforms both conventional multicast and rate-adaptive direct transmission significantly.

5. Conclusions

In this paper, we propose a cooperative layered video multicasting scheme using R-DSTC, along with packet level FEC, to enable error resilient video delivery. We optimize the transmission rates of the first and second hops as well as the STC dimension, to maximize the supportable video rate at all nodes. We show that the proposed scheme outperforms both the conventional multicast design and rate-adaptive direct transmission.

In this paper, we assume the AP knows the average channel qualities between itself and all the nodes, as well as among the nodes. In our follow-up work, we also considered how to optimize the system parameters (mainly the transmission rates) based on partial channel information, for example based only on the node count. We also studied how to provide better video quality to nodes with better channel conditions, by letting the source transmit all the video layers, and letting nodes that successfully receive the first hop transmission to forward only the base layer packets to nodes with poorer channels. These extensions are discussed in [4].

References

[1] A.Sendonaris, E.Erkip, and B.Aazhang, User cooperation diversity Part I and Part II , IEEE Transactions on Communications, vol. 51, pp. 1927-48, November 2003.

[2] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, Cooperative diversity in wireless networks: Efficient protocols and outage behavior, IEEE Transactions on Information Theory, vol. 50, no. 12, p. 3062, December 2004.

[3] B. S. Mergen and A. Scaglione, Randomized space-time coding for distributed cooperative communication, IEEE Transactions on Signal Processing, pp. 5003–5017, October 2007.

[4] O. Alay, P. Liu, Y. Wang, E. Erkip, S. Panwar, Layered Wireless Video Multicast using Randomized Distributed Space Time Codes, under review, IEEE Transactions on Multimedia.

[5] J. G. Proakis, Digital Communications, NY, McGraw-Hill, 2001.

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HAPS Ad Hoc Networks: Key Theory and Technology

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1. High altitude platforms

The increasing demand for broadband mobile communications has led to the successful and rapid development of both terrestrial and satellite wireless networks. In recent years, the high altitude platform stations (HAPS) [1-2] have been widely studied as a promising technique for providing broadband wireless communication service in the stratosphere.

HAPS has been proposed to provide wireless narrowband and broadband telecommunication and broadcasting services using either airships or high-altitude aircrafts [2]. They are usually based on quasi-stationary aerial platforms, which carry communications payloads operating at altitudes of 17 to 22km. A payload can be a base-station, or transparent transponder [2]. Each HAPS could cover an area with diameter up to hundreds kilometers depending on the minimum elevation angle accepted from the user's location [3].

HAPS has the advantages of rapid deployment, high cost-effect, small delay, large coverage footprint, broadcast/multicast capability, broad-band capability, and flexible operation, despite that it suffers some other problems [1]. It is ideal to serve new and metropolitan areas with advanced telecommunications services such as broadband access and regional broadcasting [4-5]. Although the HAPS is conceived to provide communication service, it can also be used to deliver a range of functions, such as remote sensing, environment monitoring, navigation etc.

2. HAPS ad hoc network

For the fast launch and flexible mobility of the HAPS, it is possible to construct networks with arbitrary topology in the stratosphere. Multiple HAPS could be deployed to form some specific structured networks providing comprehensive information accessing and multimedia communication services from earth to sky [5]. For this purpose, the *HAPS ad hoc network* has been proposed to construct an air-to-earth integrated network performing various tasks.

For the free mobility in the stratosphere, the HAPS ad hoc network could build a global network to cover the most areas of human activity on the earth. The HAPS networks can combine the aviation wireless communication networks in their service range and also connect the fixed or temporal terrain communication networks to form a three-dimensional (3D) ad hoc network. Since the HAPS ad hoc networks interconnect in a self-organized manner, the network can be deployed fast on demand, move to specified regions and change their topologies dynamically according to the given missions.. This network can take advantage of the HAPS application potential to extend the full services to the global scale. For civil application, it can be used to complete the functions, such as global wireless multimedia communications, disaster relief, and environment monitoring etc. And for the military applications, such a 3D ad hoc netwok can also carry out land defense warning, target spying and theater monitoring.

Since the mobility of the all communication nodes and the self-organized networking, the network has the properties of flexibility, time variability, strong heterogeneity, and hierarchical 3D architecture. So, the networking optimization and transmission administration face much more challenges.

3. Challenging problems

I: Networking on-demand

For the HAPS ad hoc network, given the task demands and environmental constraints, it is expected to make the whole network under the condition of maximum utility. In general, finding the optimized network topological structure and making the quality of service (QoS) fulfilling requirement are the primary tasks. To guarantee the better QoS, it is necessary to investigate the management on the network topology control, transmission, routing, resource allocation, etc. How to deploy the network is a task-oriented dynamic multi-objective optimization problem with time-varying constraints. The utility can be the network capacity and/or network reliability. Some natural computational methods, such as genetic algorithm, or evolutionary computation etc can be used to solve such a complicated optimization problem.

Since such a network architecture is complicated and the network structure and environment may change with time dramatically, it is very important to model the various constraints on mission requirements and constraint conditions accurately. In addition, the optimized network configuration should be adaptive to the change of the network internal and external conditions.

II. Transmission

Since the HAPS ad hoc network is dynamic, heterogeneous and complicated, the traditional network information theory, networking and relay mechanism are not enough to analyze the new network system and give full play to the advantage of the network. To this end, it is required to establish new network models and methodology to solve the above challenges.

In HAPS networks, each HAPS can cover large service area, so the HAPS networks may undertake large data transmission. However, the network topology is complex. Especially com-bining the bandwidth-limited wireless channels, the HAPS networks' capacity will become the bottleneck. The multiplexing technology has been applied to the new generation communi-cation system. It is one of the promising ways to improve the channel efficiency. In addition, the limited spectrum requires efficient resource allocation and collision resistance mechanism.

Open network environment, nodes mobility, links diversity as well as interference of coverage in the same range between wireless signals and other makes the wireless channel fading signifi-cantly. It makes the data transmission unreliable. And applying the end-to-end or hop-by-hop retransmission techniques may significantly reduce the transmission performance. The addi-tional solution for exploring the potential of the wireless communication is the cooperative com-munication technology [6]. The cooperative diversity can lead to better performance gain under fading channels [7]. It is necessary to consider how to take maximum advantage of the cooperation between nodes for improving the transmission efficiency and reliability.

Another promising cooperative communication technique is network coding [8]. It imposes the cooperative process on the packages being transmitted through the paths. It is proved that applying network coding to wireless communic-ation will result in great improvement on the throughput, energy-consuming and congestion control [9]. It is exciting to apply the network coding technique to the HAPS ad hoc networks with the aim of increasing the capacity of the network.

Routing in ad hoc network is much complicated than that in traditional network. Since such an ad hoc network is self-organized and dynamic, it is a struggle to perform the path discovery and route maintenance. However, the HAPS ad hoc network will face more difficulties. The hierar-chical structure and scalable topology are more complicated. Simply applying the available ad hoc networks routing protocols, such as AODV [10] and DSR [11] to HAPS ad hoc network will lead to poor performance. So, an intelligent routing is demanded for the HAPS ad hoc networks. Fortunately, the network coding has been introduced to improve the routing perfor-mance including delay and delivery rates [12].

4. Summary

By connecting the aviation wireless network and terrestrial networks, the HAPS ad hoc network forms a complicated 3D network topological architecture. So, it faces much more challenges including network deployment and dynamic adjustment, effective and efficient transmission. For this purpose, we have to find new theoretical analysis methods to solve these new challenges. It is believed that the modern optimization theories, network coding, cooperative diversity and intelligent routing will be the promissing techniques to fully explore the capability of HAPS ad hoc network.

References

[1] S. Karapantazis, F. Pavlidou, "Broadband com-munications via high-altitude platforms: a survey," *IEEE Communications Surveys & Tutorials*, vol.7, no.1, pp.2-31, First Qtr. 2005

[2] T. C. Tozer and D. Grace, "High-altitude platforms for wireless communications," *IEE Electronics & Com. Eng. J*, vol. 13, no. 3, pp.127-37, June 2001.

[3] C. Oestges, D. Vanhoenacker-Janvier, "Coverage analysis of a stratospheric communication system," *IET Proceedings on Microwaves, Antennas and Propagation*, vol.148, no.1, pp.45-49, Feb. 2001.

[4] D. Grace, M. H. Capstick, M. Mohorcic, et al., "Integrating users into the wider broadband network via high altitude platforms," *IEEE Trans. Wireless Commun.*, vol.12, no.5, pp.98–105, Oct. 2005.

[5] E. Cianca, R. Prasad, M. De Sanctis, et al., "Integrated satellite-HAP systems," *IEEE Commun. Mag.*, vol.43, no.12, pp. supl.33- supl.39, Dec. 2005.

[6] H. P. Frank, D. Marcos, *Cooperation in Wireless Networks: Principles & Applications*. Netherlands: Springer, Apr. 2006.

[7] A. Nosratinia, T. E. Hunter, A. Hedayat, "Co-operative communication in wireless networks," *IEEE Commun. Mag.*, vol.42, no.10, pp. 74-80, Oct. 2004.

[8] S.-Y. R. Li, R. W. Yeung, and N. Cai, "Linear

network coding, ” *IEEE Trans. Inf. Theory*, vol. 49, no. 2, pp371-381, 2003.

[9] P. Chaporkar and A. Proutiere, “Adaptive network coding and scheduling for maximizing throughput in wireless networks,” *ACM MOBICOM’07*, pp. 135-146, Montréal, Québec, Canada, September 2007.

[10] C. Perkins, E. Belding-Royer and S. Das, “Ad hoc On-Demand Distance Vector (AODV) Routing,” *RFC3651*, July 2003.

[11] David B. Johnson, David A. Maltz, Carnegie Mellon, “The dynamic source routing protocol for mobile ad hoc networks (DSR),” *RFC4728*, February 2007.

[12] J. Widmer and J.-Y. Le Boudec, “Network coding for efficient communication in extreme networks”, *Proceedings of the ACM SIGCOMM 2005 Workshop on delay tolerant networks*, pp.284-291, Philadelphia, PA, USA, August 22–26, 2005.

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Analysis of Delay in Cognitive MAC for Mobile Multimedia Communications

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1. Introduction

The current wireless communication systems are characterized by a static spectrum allocation policy according to the spectrum allocation bodies around the world, and few spectrum resources are currently available for future wireless applications. Moreover, wireless multimedia applications require significant bandwidth, some of which will be provided by third-generation (3G) services. Even with substantial investment in 3G infrastructure, the radio spectrum allocated to 3G will be limited [1]. On the other hand, a survey shows that the current spectrum utilization is much inefficient [2]. Recently, dynamic spectrum access (DSA) and cognitive radio have been proposed and have obtained more and more attention for the growing needs of improved spectrum utilization [1] [3]. Cognitive radio, that is a particular extension of software radio to employ model-based reasoning about users, multimedia content, and communications context, offers a mechanism for the flexible pooling of radio spectrum using a new class of protocols.

Therefore, it is obvious that the cognitive radio networks (CRN) require the enhancement of current PHY and MAC protocols to adopt spectrum-agile features, which allow secondary users (SUs) to access the licensed spectrum band when the primary users (PUs) are absent. Therefore, spectrum sensing for discovering the availability of the licensed spectrum band is commonly recognized as one of the most fundamental elements in CRN. Spectrum sensing could be realized as a two-layer mechanism [4]. On the one hand, the PHY-layer sensing focuses on efficiently detecting the signals of PUs to identify whether the PUs are present or not. On the other hand, the MAC-layer sensing determines when SUs should sense and which channels to sense, so as to obtain good performance in terms of sensing delay, throughput of SUs, and so on. The sensing delay is an important performance measure in CRN, especially for real-time mobile multimedia communications. Real-time multimedia communications, such as video and audio, require a bounded delay, or equivalently, a guaranteed bandwidth. Once a received real-time packet has a delay more than its delay bound, it will be considered useless and will be discarded. However, over the mobile wireless networks, a hard delay bound guarantee is practically very difficult due to the impact of the time-varying fading channels.

For two nodes to communicate with each other, they need to perform a handshake over a common control channel (CCC) before communication. However, since the CCC resource is limited, the nodes should compete for CCC with other nodes. When carrier sense multiple access with collision avoidance (CSMA/CA) mechanism is used, much time is needed, especially when the number of neighbors is large. Therefore, it is an important issue in CR-MAC protocols that how to minimize the access delay to meet the delay QoS guarantee.

In this letter, we investigate the delay when two nodes successfully access the idle licensed channel in cognitive radio networks for mobile multimedia communications, which is detailed in the following.

2. Delay analysis in CR MAC layer

Based on cognitive radio technology, the communication model between node A and node B is illustrated in Fig. 1. Before communicating with node B, node A first senses the licensed channels and searches for some idle channels for itself. Then after successfully contending for the CCC, node A sends a request-to-send (RTS), which includes the IDs of these idle channels, to node B over CCC. After sensing those channels, node B selects one channel that it also senses to be idle. Then node B sends a clear-to-send (CTS), which includes the ID of the selected idle channel, to node A.

Then, the delay when two nodes successfully access the selected idle channel is obtained by

$$T_{delay} = \sum_{i=1}^{K} \left(T_{A,s,i} + T_{A,c} + T_{B,c} + T_{B,s,i} \right) \quad (1)$$

where $T_{A,c}$ and $T_{B,c}$ denote the contention time of node A and B respectively, $T_{A,s,i}$ and $T_{B,s,i}$ denote the sensing time of node A and B, respectively, in the i-th interaction, and K is the number of interactions between nodes A and B. Generally, $T_{A,c}$ and $T_{B,c}$ are mainly determined by the number of the neighboring nodes, N_A and N_B, around nodes A and B, respectively. And the larger N_A and N_B are, the larger $T_{A,c}$ and $T_{B,c}$ are [5]. $T_{A,s,i}$ and $T_{B,s,i}$ are proportional to the number of sensed channels

$$\begin{cases} T_{A,s,i} = \tau M_{A,s,i} \\ T_{B,s,i} = \tau M_{B,s,i} \end{cases} \tag{2}$$

where τ is the time needed to sense a channel, $M_{A,s,i}$ and $M_{B,s,i}$ are the numbers of channels sensed by node A and node B, respectively. $M_{B,s,i}$ equals the number of idle channels among the $M_{A,s,i}$ channels sensed by node A. We assume each channel is idle with probability *p*, then $M_{A,s,i} = M_{B,s,i} / p$.

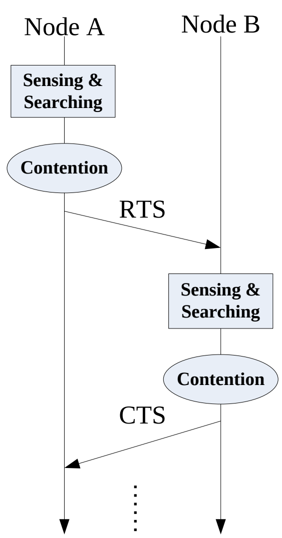

Fig. 1 communication model of two nodes based on cognitive radio technology

Based on discussion above, the delay T_{delay} is affected by the values of $M_{B,s,i}$ and *K*. Smaller $M_{B,s,i}$ and *K* result in smaller T_{delay}. However, they also lead to lower probability of successfully selecting a common idle communication channel. When the probability of successful common idle channel selection is guaranteed, smaller $M_{B,s,i}$ results in larger *K*, and vice versa, which means that a tradeoff exists between $M_{B,s,i}$ and *K* with respect to the delay T_{delay}. Therefore, appropriate $M_{B,s,i}$ and *K* should be selected to minimize the delay T_{delay}. The research problem is formulated as

$$\min_{\mathbf{M}_{B,s},K} T_{delay}$$
$$s.t. \begin{cases} P_{success} > P_{th} \\ \sum_{i=1}^{K} M_{B,s,i} \le Mp \end{cases} \tag{3}$$

where $\mathbf{M}_{B,s} = \left[M_{B,s,1}, M_{B,s,2}, \cdots, M_{B,s,K} \right]$, M is the number of licensed channels, $P_{success}$ denotes the probability of successful channel selection, and P_{th} is the threshold.

3. Conclusions

In this letter, we investigate the delay when two nodes successfully access the idle licensed channel in cognitive radio networks. Discussions show that a tradeoff exists between the number of sensed channels and the number of iterations. Hence, appropriate parameters should be selected to minimize the delay.

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References

[1] Joseph Mitola III. Cognitive radio for flexible mobile multimedia communications. In Proceedings of IEEE Mobile Multimedia Conference, pages 3–10, November 1999.

[2] Ian F. Akyildiz, Won-Yeol Lee, Mehmet C. Vuran, Shantidev Mohanty. NeXt generation/dynamic spectrum access/ cognitive radio wireless networks, A survey. Computer Networks vol. 50, no. 13, pages 2127-2159, Sep. 2006.

[3] Simon Haykin. Cognitive radio: Brain-empowered wireless communications. IEEE Journal on Selected Areas in Communications, vol. 23, no. 2, pages 201-220, Feb. 2005.

[4] Hyoil Kim and Kang G Shin. Efficient discovery of spectrum opportunities with MAC-layer sensing in cognitive radio networks, IEEE Transactions on Mobile Computing, vol. 7, no. 5, pages. 533-545, May. 2008.

[5] G. Cheng, W. Liu, Y. Li, and W. Cheng, "Joint on-demand routing and spectrum assignment in cognitive radio networks," in Proceedings of the IEEE ICC Conference, 2007.

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Reducing the Channel Switching Delay in IP-based Multi-channel Streaming

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1. Introduction

The rapid growth in network speed and bandwidth has empowered audio/video streaming services such as Internet TV and IPTV [1]. Most streaming services broadcast a large number of channels from which a user may choose to watch. These multi-channel streaming services enable viewers to change channels at will. However, the channel switching delay via the Internet, which is the amount of time from which the demand for a new channel is issued until the request is satisfied, is typically quite long. Long channel switching time degrades the quality of experience (QoE) of IP-based multi-channel streaming. Reducing this channel switching delay is an important problem.

So far, most streaming technologies are based on unicast communications between a server and a client. However, as an alternative to unicast-based streaming communications which increases the traffic load of the network and server, multicast-based streaming communications has been developed. In IP multicast, which is one type of multicast-based communications, routers make copies of the streaming packets and forward them to other routers and end-nodes. IP multicast, which requires specialized routers, incurs a significant cost. As an alternative to IP multicast, Application Layer Multicast (ALM) [2] has recently been proposed. In ALM, copies and deliveries of streaming packets are done by end-nodes. Since ALM does not require any specialized equipment, it is quite easy to deploy. However, unreliable end-nodes may degrade the entire quality of service (QoS).

In this position article, we will give a brief overview of some of the existing techniques to reduce the channel switching delay based on multicast techniques, and provide a glimpse into the future of multi-channel streaming technologies. Readers are referred to various references for further studies.

2. Channel Switching Delay

In IP multicast and ALM, multicast groups are constructed to distribute the content of each channel, and nodes may join the multicast group of their desired channels. Since network bandwidth is limited, nodes cannot join all of the multicast groups and receive streams from all channels. Therefore, to preserve resources, nodes should initiate an efficient participation/leaving procedure with the multicast group when they switch channels.

According to [3], as for the case of IPTV, the channel switching delay depends on the following: the command processing time, the network delay, and the Set Top Box (STB) delay, which mainly consists of the buffering delay and the Moving Picture Experts Group (MPEG) decoding delay, as shown in Fig. 1.

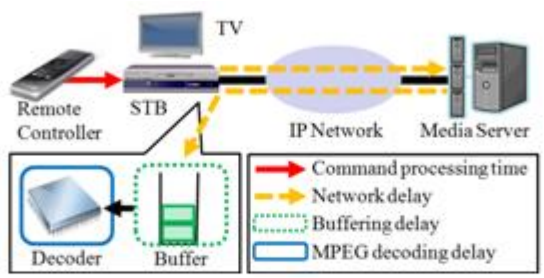

Fig. 1. Components of making up the channel switching delay in IPTV.

A viewer requests STB to switch channel by using a remote controller. Time until this request is accepted is referred to as the command processing time. The network delay is the time interval between the transmission of the join message and the reception of the first multicast packet of the requested channel. The buffering delay is the time from the first multicast packet is received until the buffer reaches a threshold prior to the transmission of the video signal to the decoder function. The threshold is designed to circumvent network jitter. The MPEG decoding delay is the time interval required by the decoding process.

3. Existing Proposals

Several approaches have been proposed to reduce the channel switching delay in multi-channel streaming, which can be categorized into two groups: IP multicast based and ALM based.

3.1. IP Multicast Based Approach

One approach to reducing the channel switching delay is by predicting channel requests and preparing reception of additional channels [4]–[6]. In [4], a viewer of channel number N joins multicast groups of channel number N -1, N and N +1. This allows for smooth "channel surfing" between adjacent channels. In [5]–[6], the viewer's profile, history, and other information are used to predict the next channel.

Fast channel switching based on reducing the decoding delay was studied in [7]–[11]. MPEG-2 and H.264/MPEG AVC video coding standards encode and transmit videos by using a Group Of Pictures (GOP) model where the video stream is defined as a series of interdependent frames. The video is encoded into a series of I, P, and B frames. The I frame contains the reference image and the P and B frames contain only difference information about the previous frame. Therefore, when a node switches channels, decoding is impossible until the next I frame is obtained. In [7], additional lower quality I frames are sent in addition to the normal quality coded pictures, as shown in Fig. 2. Responsive channel switching is achieved since I frames are frequently available. Synchronization Frames for Channel Switching (SFCS) [8] is another technique by using additional I frames, and is similar to that of [7]. Readers are referred to [9] for further studies on the trade-off between the channel switching delay and network efficiency.

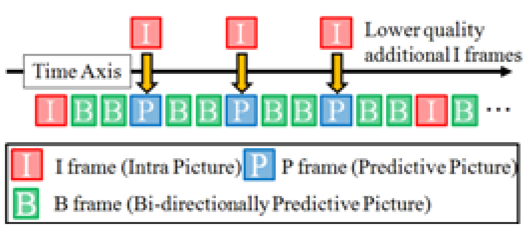

Fig. 2. Additional I frames to the normal quality coded pictures.

By decreasing the buffer delay time, the channel switching delay is also decreased. For example, an accelerator server [10], which can send a copy of the original stream with a fixed delay, is set up for each channel. The viewer of channel G receives streaming packets from both the main server and the accelerator server until the initial play-out buffer is filled up, as shown in Fig. 3. As a result, the channel switching delay introduced by the initial buffering delay can be reduced.

In another proposal, Multicast Assisted Zap Acceleration (MAZA) [11], each channel has several time-shifted sub-channels. When a viewer switches the channel, he can select and join the sub-channel which is closest to sending the next I frame, as shown in Fig. 4.

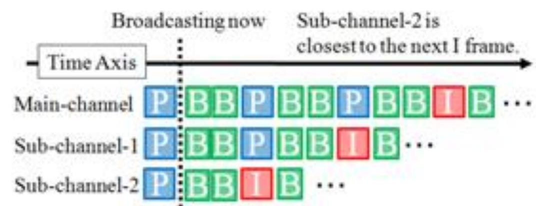

Fig. 3. Decreasing buffer delay time by the accelerator server.

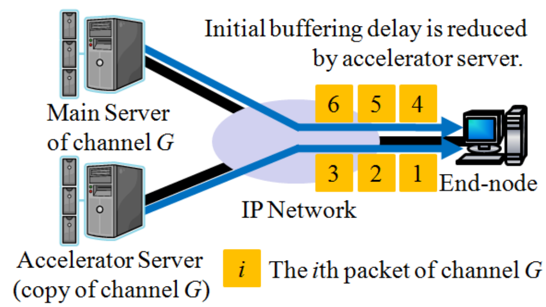

Fig. 4. Multicast Assisted Zap Acceleration.

3.2. ALM Based Approach

A few ALM based techniques have been proposed for multi-channel streaming [12]–[14], but the authors left the channel switching delay issue as their future works. One recent work, View Upload Decoupling (VUD)[15]–[16], did consider the channel switching delay. In VUD, nodes not only join the channel they are watching, but they also join several other channels according to the amount of unused available bandwidth. Since they receive additional channel information as shown in Fig. 5, the channel switching delay is reduced.

4. Multi-channel Streaming over Heterogeneous Networks

Most existing approaches require a large amount of node bandwidth for channels which are not even viewed. However, in a real network, each node's available bandwidth is heterogeneous and limited. Therefore, in multi-channel streaming, an efficient approach which not only reduces the channel switching delay but also reduces bandwidth usage must be developed. Network-aware Hierarchical Arrangement Graph (NHAG) [17] is an ALM based single-channel streaming approach applied to the participatory nodes' available bandwidth and dynamic networks. Among ALM based approaches, NHAG demonstrates robustness and efficient utilization of bandwidth for end-nodes, and can be potentially extended to reduce the channel switching delay.

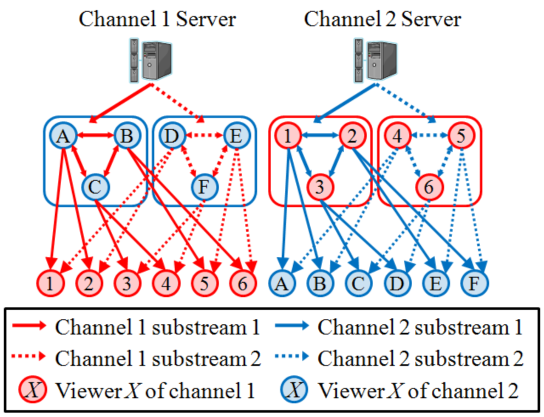

Fig. 5. View Upload Decoupling.

5. Conclusion

Audio/video multi-channel streaming is becoming widespread across the Internet. However, the channel switching delay still poses a significant issue. In this position article, we have described several existing approaches to reduce the channel switching delay based on IP multicast and Application Layer Multicast. These approaches are effective at reducing the channel switching delay, but require additional bandwidth from the network. Minimizing the channel switching delay with the minimum additional network resource is critical for future multi-channel streaming.

References

[1] J. Maisonneuve, M. Deschanel, J. Heiles, W. Li, H. Liu, R. Sharpe, and Y. Wu, "An overview of IPTV standards development," *IEEE Transactions on Broadcasting*, vol. 55, no. 2, pp.315-328, Jun. 2009.

[2] M. Hosseini, D. T. Ahmed, S. Shirmohammadi, and N. D. Georganas, "A survey of application-layer multicast protocols," *IEEE Communications Surveys & Tutorials*, vol. 9, no. 3, pp. 58-74, 2007.

[3] C. Cho, I. Han, Y. Jun, and H. Lee, "Improvement of channel zapping time in IPTV services using the adjacent groups join-leave method," in *Proc. IEEE International Conference on Advanced Communication Technology*, pp. 971-975, Feb. 2004.

[4] C.-C. Sue, C.-Y. Hsu, Y.-S. Su, and Y.-Y. Shieh, "A new IPTV channel zapping scheme for EPON," in *Proc. IEEE International Conference on Ubiquitous and Future Networks (ICUFN 2009)*, pp.131-136, Jun. 2009.

[5] M.Z. Ahmad, J. Qadir, N.U. Rehman, A. Baig, and H. Majeed, "Prediction-based channel zapping latency reduction techniques for IPTV systems - a survey," in *Proc. IEEE International Conference on Emerging Technologies (ICET 2009)*, pp. 466-470, Oct. 2009.

[6] Y. Kim, J. K. Park, H. J. Choi, S. Lee, H. Park, J. Kim, Z. Lee, and K. Ko, "Reducing IPTV channel zapping time based on viewers surfing behavior and preference," in *Proc. IEEE International Symposium on Broadband Multimedia Systems and Broadcasting*, pp.1-6, Mar. 2008.

[7] J. M. Boyce and A. M. Tourapis, "Fast efficient channel change [set-top box applications]," in *Proc. IEEE International Conference on Computers in Education Digest of Technical Papers*, pp. 12, Jan. 2005.

[8] U. Jennehag and S. Pettersson, "On synchronization frames for channel switching in a GOP-based IPTV environment," in *Proc. IEEE Consumer Communications and Networking Conference*, pp. 638-642, Jan. 2008.

[9] H. Joo, H. Song, D.-B. Lee, and I. Lee, "An effective IPTV channel control algorithm considering channel zapping time and network utilization," *IEEE Transactions on Broadcasting*, vol. 54, no. 2, pp. 208-216, Jun. 2010.

[10] C. Sasaki, A. Tagami, T. Hasegawa, and S. Ano, "Rapid channel zapping for IPTV broadcasting with additional multicast stream," in *Proc. IEEE International Conference on Communications (ICC 2008)*, pp. 1760-1766, May 2008.

[11] Y. Bejerano and P. V. Koppol, "Improving zap response time for IPTV," in *Proc. IEEE INFOCOM*, pp. 1971-1979, Apr. 2009.

[12] X. Liao, H. Jin, Y. Liu, L. M. Ni, and D. Deng, "AnySee: peer-to-peer live streaming," in *Proc. IEEE International Conference on Computer Communications (INFOCOM)*, pp. 1-10,Apr. 2006.

[13] G. Tan and S.A. Jarvis, "Inter-overlay cooperation in high-bandwidth overlay multicast," in *Proc. International Conference on Parallel Processing (ICPP)*, pp. 417-424, Aug. 2006.

[14] X. Jin, S.-H.G. Chan, W.-C. Wong, and A.C. Begen, "A distributed protocol to serve dynamic groups for peer-to-peer streaming," *IEEE Transactions on Parallel and Distributed Systems*, vol. 21, no. 2, pp. 216-228, Feb. 2010.

[15] D. Wu, C. Liang, Y. Liu, and K. Ross, "View-upload decoupling: a redesign of multi-channel P2P video systems," in *Proc. IEEE INFOCOM*, pp. 2726-2730, Apr. 2009.

[16] D. Wu, Y. Liu, and K. W. Ross, "Modeling and

analysis of multichannel P2P live video systems," to appear in *IEEE/ACM Transactions on Networking*.

[17] M. Kobayashi, H. Nakayama, N. Ansari, and N. Kato, "Robust and efficient stream delivery for application layer multicasting in heterogeneous networks," *IEEE Transactions on Multimedia*, vol. 11, no. 1, pp. 166-176, Jan. 2009.

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Multimedia over Sensor Networks

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1. Introduction

The use of multimedia sensor nodes is motivated by the intrinsic feature of scalar data collection in traditional sensor networks, where scalar sensory data (e.g., temperature, humidity, air pressure, etc) is hard to describe many complicated events and phenomena. Since multimedia sensor nodes can provide more comprehensive information such as image or audio stream, multimedia sensor networks start to be widely applied in many industrial applications. Consequently, multimedia streaming over wireless sensor networks became an important and challenging research issue.

2. The Untouched Research Problem

Ever since the appearing of the concept of wireless multimedia sensor networks e.g., [1], [2], and [3], lots of research efforts had been conducted towards the optimal multimedia streaming over wireless sensor networks. Most of these researches focus on the design of cross-layer optimized schemes, e.g., [4], [5], and [6]. These cross-layer optimization schemes can successfully optimize the multimedia stream data transmission between a single source node and the base station, e.g., [6] provides a cross-layer scheme aiming at maximizing the data gathering from a single multimedia node within an expected network lifetime. However, the research problem for transmitting the multimedia streams from multiple multimedia source nodes is still untouched as shown in Figure 1.

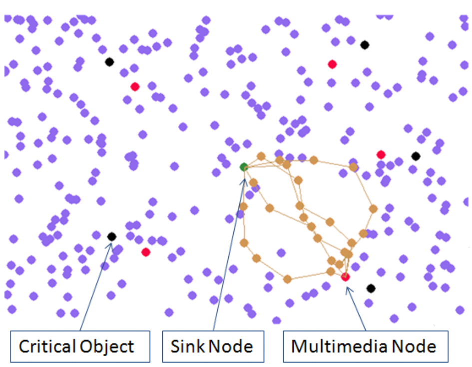

Fig. 1. An example: Five multimedia sources are deployed in the network field to monitor five critical objects. For each source node, at least five transmission paths are needed for sending the large volume of multimedia stream data.

3. Dynamic Hole and Competing Area

When transmitting multimedia streams in sensor networks, the used relay nodes in the transmission paths generally cannot be shared with other source nodes for constructing new path, and thus forming a dynamic hole when a number of closely deployed relay nodes are fully occupied. However, if all the multimedia source nodes want to transmit their stream data at the same time, some neighboring source nodes will have to compete with each other for the use of the number-limited sensor nodes as relay nodes to construct their multiple routing paths. As shown in Fig. 2, the overlapped area of neighboring source nodes' dynamic holes can be considered the competing area. This kind of competition among neighboring source nodes can cause the difficulty to guarantee the global fairness, which means to equally gather the stream data from different source nodes. We believe that some considerable research effort should be invested into this research issue, and probably the using of game theory can help.

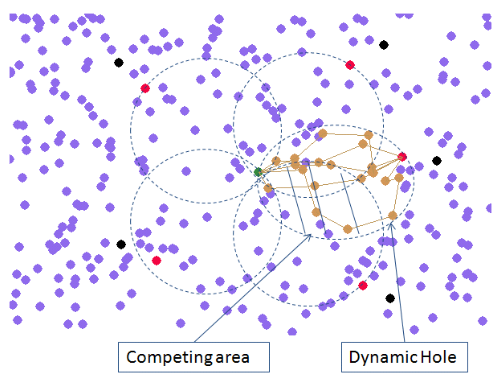

Fig. 2. The example of the dynamic hole and the competing area.

4. Mobility with Multimedia Sensor Networks

Mobile sensor networks [7] have received a lot of research attention in the past few years, and it is mostly considered as a parallel research trend of multimedia sensor networks. As shown in Figure 3, the emerging new hardware platform gives us a sense that these two parallel researches have a trend to be merged into another research scope entitled as *Mobile Multimedia Sensor Networks (MMSN)*. For example, if we further consider that both the multimedia source nodes and the base station are moveable, then the above presented problem in Section 3 will need an even more comprehensive solution to optimize the locations of mobile nodes so that the fairness on the data collection and the cost on the data transmission can be further optimized.

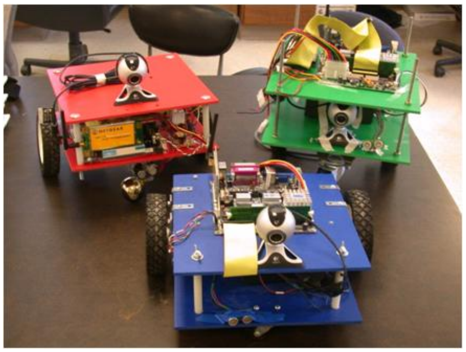

Fig. 3. An example of the mobile multimedia sensor nodes (Note: this picture is obtained from AICIP laboratory at the Electrical Engineering and Computer Science Department of the University of Tennessee, USA).

5. MMSN Challenging Research Issues

We define the *Mobile Multimedia Sensor Networks* as: using a number of mobile multimedia sensor nodes in a sensor network to enhance the sensor network's capability for event description. Due to the merging of mobility into multimedia sensor networks, a number of challenging research issues can appear in both the data communication and data management aspects: 1) Multimedia streaming in sensor networks generally needs multiple stable paths for transmission, if either the source node or the base station can move, it will be very hard to maintain stable multiple transmission paths in the sensor network; 2) In the case of caching multimedia stream in the mobile sensor networks, it will be very difficult to use traditional caching methods, since the multimedia stream data has large size, and needs the in network collaboration among small sensors, since the storage in sensors is normally small in size.

6. Conclusions

Multimedia streaming in wireless sensor networks is an important research issue, since multimedia information has the irreplaceable role for event description. Research efforts of this particular community should take a look at the merged application area, where both the mobility and multimedia functions are necessary. In this paper, we highlighted a typical untouched research problem to introduce the concept of *Mobile Multimedia Sensor Networks*, and presented a few its research challenging issues.

Acknowledgement

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References

[1] Eren Gurses, Ozgur B. Akan. Multimedia Communication in Wireless Sensor Networks. In *Ann Telecommun*, 60(7-8), pp.799-827, 2005.

[2] Ian F. Akyildiz, Tommaso Melodia, Kaushik R. Chowdhury. A Survey on Wireless Multimedia Sensor Networks. In *Computer Networks*, 51(4), pp.921-960, 2007.

[3] Misra, S., Reisslein, M., Xue, G.: A Survey of Multimedia Streaming in Wireless Sensor Networks, in *IEEE Commun Surv Tutor*, 10(4), pp.18-39, 2008.

[4] Navrati Saxena, Roy Abhishek, Jitae Shin. Cross-Layer Algorithms for QoS Enhancement in Wireless Multimedia Sensor Networks. In IEICE Transaction on Communications, E91-B(8), August, 2008.

[5] Tommaso Melodia, Ian F. Akyildiz. Cross-Layer Quality of Service Support for UWB Wireless Multimedia Sensor Networks. In INFOCOM'08: Proceedings of the 27th IEEE Conference on Computer Communications, Mini-Conference, Phoenix, Arizona, April, 2008.

[6] Lei Shu, Manfred Hauswirth, Yan Zhang, Jianhua Ma, Geyong Min, Yu Wang. Cross Layer Optimization on Data Gathering in Wireless Multimedia Sensor Networks within Expected Network Lifetime. In Springer Journal of Universal Computer Science (JUCS), 2010.

[7] Donghua Deng, Qun Li. Communication in Naturally Mobile Sensor Networks. In WASA'09: Proceedings of the 4th International Conference on Wireless Algorithm, Systems, and Applications, Boston, MA, USA, August 2009.

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LEM: a Cooperative and Self-Organizing Flow Relaying Middleware for Multimedia Continuity in Dense Hybrid Wireless Networks

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1. Introduction

The recent advances in wireless client devices, that host heterogeneous wireless technologies spanning from IEEE 802.11 (WiFi) and Bluetooth (BT) to cellular 3G and beyond, and the crucial role of multimedia communications in our society are motivating new multimedia provisioning scenarios. In particular, industrial interest has recently started to concentrate on the opportunities of tailoring multimedia content delivery depending on client location, with different goals, from personalized location-dependent advertising/marketing to enhanced forms of touristic assistance. Those services show their main benefits when applied to highly populated regions where specific contents should be distributed to geographically bounded Areas of Interest (AOIs), e.g., personalized and different promotional videos toward the areas used by different exhibitors in an exhibition pavilion.

Despite their recognized potential benefits, the development and deployment of those new classes of AOI-targeted multimedia services are still challenging tasks, also due to their quality requirements, e.g., data arrival time, jitter, and packet losses. In addition, densely populated spots introduce new challenges: i) they are typically short-termed and that makes it very costly to plan and deploy in advance needed network/provisioning infrastructures; ii) fixed wireless infrastructure requires installation of power lines and wired connections to the Internet, which is unfeasible in several cases; iii) node mobility further exacerbates the above issues, especially the seamless provisioning of service flows with quality and continuity requirements.

This letter overviews the research work we are recently doing for an original self-organizing middleware for seamless multimedia delivery in dense wireless regions with AOIs (dense AOIs). We claim that the proposed solution is relevant for three primary technical contributions. First, it automatically and continuously re-organizes dense AOI network topology using a lightweight localization technique (based on received signal strength indication - RSSI, infrastructure-less, and anchor-free). Second, it takes advantage of dense network population and wireless technology diversity (rather than considering it a technical issue) to achieve the needed positioning accuracy and multimedia distribution scalability. Third, it shows how it is possible to effectively exploit mobile relays, automatically re-elected within the community of dense AOI nodes, as both markers for AOI identification and communication gateways for other nodes in the same neighborhood. Here, we rapidly describe the open-source implementation of our middleware, called Localized rElay-based mobile Multimedia (LEM), and a selection of relevant experimental results about node mobility monitoring, dynamic relay determination, and client-side multimedia buffering. Additional information, further experimental results, and the LEM prototype code are available at the project website [1].

2. LEM Motivations and Related Work

The primary goal of LEM is to enable seamless provisioning of self-organizing personalized multimedia services toward dense AOIs notwithstanding node mobility; the central idea is to exploit the collaboration of peers (and in particular of dynamically elected relay nodes) in order to fully exploit both the dense scenario assumption and the rich availability of (often under-utilized) resources at mobile terminals.

First, let us remark that our solution shows its main benefits and is explicitly optimized for localized ad-hoc wireless networks that include a large number of nodes in a small area at the same time and where any node has an average number of one-hop neighbors (node density) almost invariant during long time intervals [2]. We are especially interested in hybrid wireless networks in which some nodes, equipped with multiple wireless connection types, can meld together different wireless technologies and modes, namely ad-hoc and infrastructure, working as bridges and acting as relays for their ad-hoc neighbors in the dense network. For instance, a typical scenario is a BT dense neighborhood connected through a WiFi-equipped node to a WiFi infrastructure. As for the dense AOI, more formally, we define it as a limited logically bounded region with diameter two hops within the dense hybrid wireless network.

One primary idea in LEM is to exploit

approximated and lightweight estimations about relative node positions to take proper management decisions on its dynamic collaborative relays. In particular, to enable completely decentralized and anchor-free localization, LEM realizes specific protocols to reorganize the dense AOI network topology. LEM includes fully decentralized localization techniques (based on RSSI, infrastructure-less, and anchor-free) to locate the relay (centermost dense AOI node) and to choose mobile clients in a well-balanced structure (circular crown) around the relay, so to facilitate relay movement monitoring. When our solution estimates that the relay is going to abandon its AOI center, it proactively triggers relay re-election and automatically manages the multimedia flow handoff process from the old to the new relay (relay handoff management) to minimize data losses and delays. Relay central position is important for at least two main reasons: i) to proactively monitor and react to relay exits from the dense AOI; ii) to have a relative (although) mobile anchor-point that demarks the center of the dense AOI. In order to locally self-monitor relay mobility, we also dynamically select some nodes in a circular crown around the relay, neither too close nor too far, as additional anchor points to effectively predict and counteract relay movements outside the AOI, in any direction. To enable this "crown-operated" relay monitoring, we exploit client nodes in the dense AOI: our client election protocol reshapes AOI network topology by (re-)placing clients in a well-forged circular crown around the relay, by estimating positions in a lightweight way via RSSI values extracted from exchanged multimedia data packets (coarse-grained evaluation of reciprocal distances).

Fig. 1 sketches the deployment and interactions of LEM nodes in a common service scenario: relay node (green); client nodes in the circular crown around the relay (dark green); and other regular nodes roaming around in the AOI (light green). For sake of space limitations, in the remainder of this letter we will focus on the most common unidirectional down-stream scenario where AOI clients are only willing to get multimedia contents and the relay downloads them from multimedia servers on the wired network via an Access Point (AP) – for communication only and not for localization purposes. Continuous and dashed lines represent, respectively, server-to-relay (via WiFi) and relay-to-client (via BT) data paths. The relay handoff occurs when the (old) relay node moves away from the AOI center and it is necessary to quickly find a (new) peer node to replace it, by exchanging session state from the old to the new relay (green continuous line).

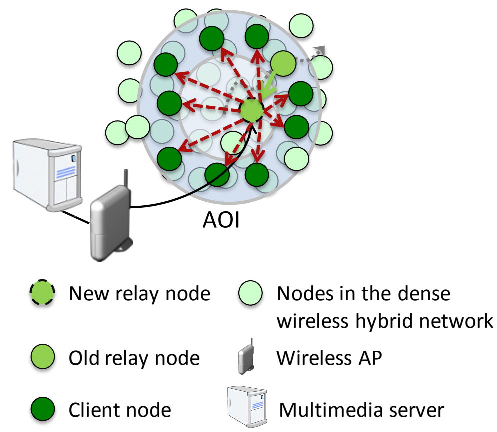

Fig. 1. Common AOI scenario with relay handoff management from old to new relay.

Let us rapidly conclude this section with a short related work pointing out the recent academic/industrial interest in the field and the original technical elements of LEM if compared with the related literature. About decentralized and cooperative localization, several wireless positioning solutions have been proposed in the last years ([3] is a good survey), also to automatically generate node position maps without external anchors and to locate traversing mobile nodes, such as in multidimensional scaling techniques for mobile location [4]. Those proposals inspired LEM protocols for dense AOI maintenance and relay election, even if LEM scenario is much more dynamic with higher node mobility; as a consequence, LEM solutions do not strive to achieve high localization accuracy, but rather to guarantee low protocol overhead. Another very close research area is multimedia delivery in hybrid infrastructure/ad-hoc meshes integrated with (mobile) relay networks. First work was aimed to extend infrastructure coverage via (usually fixed) 1/2-hops relay chains [5]. Very recently, a few relevant activities have started to investigate the opportunities associated with the combination of peer-to-peer applications, the effective allocation/management of resources over physical/logical mesh partitions, and the possibility to dynamically integrate wireless meshes with opportunistic overlays [6]. However, while relevant efforts have explored multimedia handoff in infrastructure wireless networks from the mobile node perspective, research on mobile relays has primarily considered store-and-forward streaming techniques up to now, rather than dealing with the more challenging issue of relay handoff management as LEM does [6].

3. RSSI-based Proactive Relay Re-election for Streaming Continuity

In the remainder of this letter, we specifically focus on two technical challenges that LEM originally addresses: relay handoff prediction and, most important, seamless flow streaming during relay handoff. For further insights about other LEM aspects, such as localization protocols for circular crown formation (client election) and centermost relay election, interested readers may refer to the project Web site [1].

Two core LEM components collaborate to address the above issues; Fig. 2 shows main coordination steps among all main distributed LEM entities with continuous and dashed lines representing, respectively, data and control flows. The first component is the RSSI-based relay handoff predictor (RHP) to proactively trigger relay handoff management; it executes at both client and relay. The client side obtains RSSI data from datalink managers (gathered from incoming multimedia packets), massages them to be interoperable over a wide range of BT network cards/drivers, and sends RSSI updates to the relay (step 1, in Fig. 2). The relay side receives RSSI updates from clients and uses our lightweight RSSI-Grey Model Predictor (RSSI-GMP) to melt them together and to estimate relay handoff predictions on the basis of a finite series of RSSI values monitored in the recent past [1]. The second component, the Multimedia streaming & continuity (MMSC), controls the relay handoff process and smoothes relay handoff latency and packet losses; it is also deployed at both client and relay. MMSC implements the relay handoff protocol and ensures data continuity via a two-level buffering solution, with one buffer stored at the client and one at the relay. When a relay handoff occurs, the old relay promptly transmits buffered data and client session information to the new (dynamically elected) relay and clients continue to sustain the playout by using their local buffers (step 3). After that transfer, the new relay (relay-side MMSC) promptly re-establish ongoing connections with its server and clients, clients detach from the old relay, and the new relay promptly re-fills their client-side buffers by re-transmitting packets possibly lost during the handoff (step 4). A client-side MMSC playout stub uses the data stored in the client buffer to continuously render the multimedia flow at client nodes.

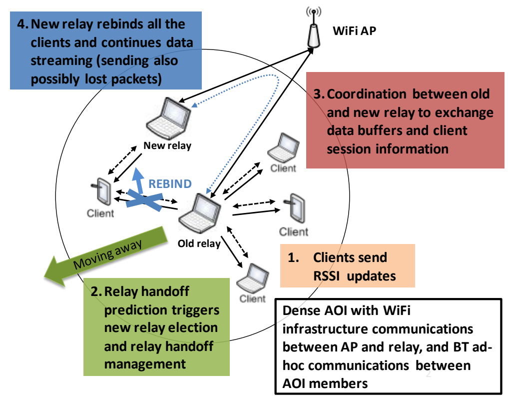

Fig. 2. LEM proactive management of relay handoff.

Delving into finer technical details, relay-side MMSC is responsible of and controls all multimedia flow transmissions within the AOI. To obtain high throughput and minimize interferences, it transmits data in bursts and adopts an earliest deadline first schedule i) to meet client-side playout deadlines by avoiding client buffer exhaustion (namely buffer underflow) and ii) to avoid relay-side buffer saturation (namely buffer overflow). Fig. 3 shows the function used to evaluate the next transmission time.

CalculateNextTransmissionTime

Objective is to avoid: i) client buffer underflow and ii) relay buffer overflow

- L_{Ci} = Current filling level of the i-th AOI client buffer (byte)
- CUT = Client buffer underflow threshold (byte)
- FL = Frame length (byte)
- BR = Multimedia flow byte rate (byte/sec)

- L_{Ri} = Current filling level of the relay buffer devoted to the i-th client (byte)
- ROT = Relay buffer overflow threshold (byte)
- FL = Frame length (byte)
- BR = Multimedia flow byte rate (byte/sec)

$$\mathrm{cDuration}_i = \begin{cases} (L_{Ci}-\mathrm{CUT})*\mathrm{FL}/\mathrm{BR}, & \text{if } L_{Ci}>\mathrm{CUT}; \\ 0 & \text{otherwise} \end{cases} \qquad \mathrm{rDuration}_i = \begin{cases} (\mathrm{ROT}-L_{Ri})*\mathrm{FL}/\mathrm{BR}, & \text{if } \mathrm{ROT}>L_{Ri}; \\ 0 & \text{otherwise} \end{cases}$$

$$\mathrm{nextTransmissionTime} = \mathrm{currentTime} + \min_{\text{(for all Ci in the AOI)}}(\mathrm{cDuration}_i,\ \mathrm{rDuration}_i)$$

Fig. 3. Evaluation of the next transmission time.

We take into account current client-/relay-side buffer filling levels (effective usage of the total buffer size) and, for sake of simplicity, we assume the same data flow rate (mean data frame length and flow byte rate) for all clients; in addition, we introduce two security thresholds, called respectively Client buffer Underflow Threshold (CUT) and Relay buffer Overflow Threshold (ROT) to guarantee streaming continuity notwithstanding possible unpredictable delays due to operating system multi-tasking, limited bandwidth, etc.

4. Experimental Results

We have tested and evaluated the performance of LEM in a deployment scenario with 3 clients, 1 relay, and 1 multimedia server. This (limited) real testbed is aimed to assess the runtime behavior of our implementation; at the same, we are also thoroughly verifying all main LEM protocols running extensive simulations with higher node numbers and different node velocities. The clients, the relay, and the multimedia server are implemented in Java. We use the Java Media Framework (JMF) for RTP-based audio streaming. In the following, we report experimental results, averaged over a hundred relay handoff cases, while provisioning an Audio on Demand (AoD) service (WAV-encoded flows with constant frame rate = 50 frames/s and 352Kbps bandwidth). As regards low-level system monitoring, BT RSSI can be obtained through the specific tool (hcitool) of the BlueZ stack for Linux [1]. Client nodes are Linux laptops equipped with different BT cards: ASUS Bluetooth and Mopogo Bluetooth. The relay, in addition to the BT interface hosts also an Orinoco Gold WiFi card to enable communications between the relay and the fixed multimedia server. Multimedia server execute on standard Linux v2.6 with 1.8 GHz processors and 1024MB RAM.

The first experiments demonstrates the ability of RSSI-GMP to effectively predict forthcoming relay handoff events. Without any loss of generality and for the sake of simplicity, we consider the relay as the only mobile node; during our experiment, the relay moves away from the center towards the borders of the AOI and then back to the center, while the three AOI clients, deployed around the relay to emulate the usual AOI deployment, are static. Fig. 4 and Fig. 5 show the timelines, respectively, of the RSSI monitored at one of the clients (other clients show a similar trend) and of the aggregated RSSI estimated by RSSI-GMP at the relay. Client-side RHP extracts the RSSI values expressed in heterogeneous RSSI scales and map them into an internal LEM RSSI scale, from 0 for near nodes to 17 for distant nodes, without employing any filtering/prediction technique (see Fig. 4).

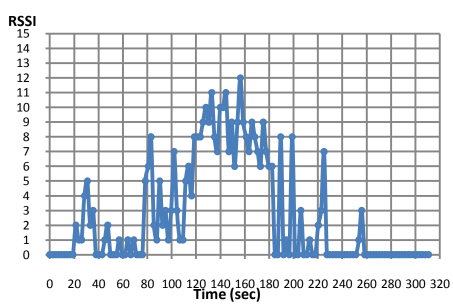

Fig. 4. RSSI monitored at client side.

RSSI-GMP, instead, is able to aggregate and to smooth incoming RSSI updates from all clients, and it successfully predicts future RSSI trends due to relay movement. For instance, the RSSI increase at 80s in Fig. 5 (relay move-away) anticipates the same increasing trend, even if with more noise due to the lack of filtering, starting at 94s in Fig. 4. RSSI-GMP proactively triggers relay handoff management as the predicted RSSI value overcomes the so-called relay handoff threshold that was experimentally fixed to 7.

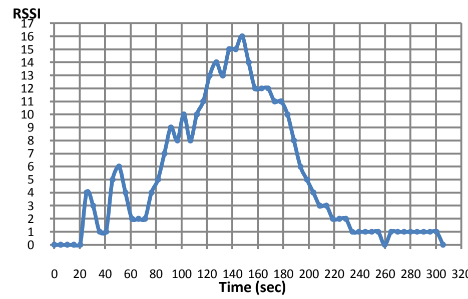

Fig. 5. Aggregated RSSI estimated by RSSI-GMP at the relay.

The second experiment assesses the delays for relay re-election and session rebind; the total sum amounts to a mean value of 3.3s. That long time is mainly due to the long BT-related node inquiry and connection latencies, and confirms the need for proactive management to avoid multimedia streaming/session interruption. The third and last experiment proves that our proactive client-side buffer management can grant session continuity even in the most challenging case of two consecutive and close relay handoff events. Fig. 6 shows the client buffer filling level (expressed as filling up percentage over buffer length). During the two handoff events, respectively around 10s and 25s (vertical arrows in Fig. 6) the buffer level decreases, but it is always sufficient to sustain audio playout, and after handoffs LEM fast (re-)transmission permits to promptly refill the buffer. In other words, client-side MMSC playout stub has always a sufficient number of frames to provide high-quality audio playout without interruptions.

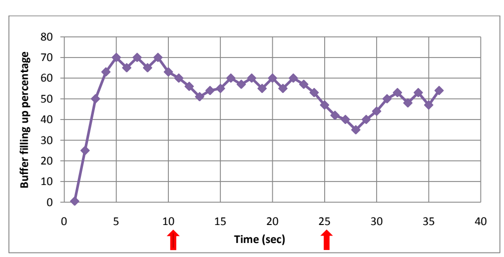

Fig. 6. Client-side buffer filling level timeline.

5. Conclusions

The research work accomplished within the LEM project demonstrates the suitability of dynamic mobile relay collaboration for seamless multimedia streaming in hybrid wireless networks with dense AOIs. The reported results show that it is possible to predict relay handoff by only exploiting lightweight estimations on mutual node positions and thus to provide clients with seamlessly continuous data flows. The encouraging results obtained so far are motivating our current research along two primary directions. We are extending our LEM prototype to support also 3G cellular and UMTS for the infrastructure-relay communication trunk. In addition, we are extending our work on ns2 simulations to quantitatively evaluate the LEM behavior when AOI nodes roam according to different mobility models.

References

[1] LEM Project Website: http://lia.deis.unibo.it/Research/LEM/

[2] P. Bellavista, A. Corradi, E. Magistretti, "Lightweight Autonomic Dissemination of Entertainment Services in Widescale Wireless Environments", *IEEE Communications Mag.*, vol. 43, no. 6, Jun. 2005, pp. 94–101.

[3] A. Dogandzic, J. Riba, G. Seco, A.L. Swindlehurst (Guest Ed.), "Positioning and Navigation with Applications to Communications", Special Issue on Positioning in Wireless Networks, *IEEE Signal Processing Mag.*, vol. 22, no. 4, Jul. 2005, pp. 10–11.

[4] Z. Chen, H. Wei, Q. Wan, S. Ye, and W. Yang, "A Supplement to Multidimensional Scaling Framework for Mobile Location: A Unified View", *IEEE Trans. on Signal Processing*, vol. 57, no. 5, May 2009, pp. 2030–2034.

[5] D. Cavalcanti, D. Agrawal, C. Cordeiro, Bin Xie, A. Kumar, "Issues in integrating cellular networks WLANs, AND MANETs: a futuristic heterogeneous wireless network", *IEEE Wireless Communications Mag.*, vol. 12, no. 3, Jun. 2005, pp. 30–41.

[6] N. Banerjee, M.D. Corner, D. Towsley, B.N. Levine, "Relays, Base Stations, and Meshes: Enhancing Mobile Networks with Infrastructure", *ACM Int. Conf. on Mobile Computing and Networking (MobiCom)*, 2008, pp. 81–91.

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