Center for Embedded Systems (CES)
Request for Proposals Template – YEAR 8

DUE: FRIDAY, APRIL 15, 2016, by 11 p.m.

TITLE:	Internet-of-Things Applications Development for Private LTE Small-Cell Networks			
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DEPT:	ECE	**SCHOOL:** SIU		

ABSTRACT: (250 or fewer words)

We are witnessing the dawn of a new era of Internet of Things (IoT; also known as Internet of Objects). Generally speaking, IoT refers to the networked interconnection of everyday objects, which are often equipped with ubiquitous intelligence. Projections say that by the year 2020, 16 billion dynamic-networked devices will be deployed, and interact with the real world simultaneously generating huge quantities of data. Smart building, self-driving cars, house monitoring and management, city electricity and pollution monitoring are some examples where dynamic networked real-time systems are deployed. This bloom of dynamic networked devices was also a result of new network services. With lower latency and higher bandwidth than its predecessor 3G networks, the latest cellular technology 4G LTE has been attracting many new users. However, the interactions among applications and network transport protocol still remain unexplored. In this project, we propose methodologies for interfacing, controlling and monitoring IoT devices in industrial settings over private LTE small-cell networks over 3.65 GHz frequency band.

PROBLEM:

The value of dynamic networked real-time systems is hidden in the increased value of information created by the number of interconnections and the transformation of the processed information into knowledge. A lot of research has been done on intelligent decision-making algorithms, machine learning and management techniques resulting in remarkable results. However, the growing complexity of these systems, due to the high number of interconnected components and complex iterations among devices, will be unmanageable, and will obstruct the development of new services and applications.

4G LTE is the latest deployed cellular network technology that provides high-speed data services for mobile devices with advertised bandwidths matching and even exceeding the home broad band network speeds. Recent work [1] has demonstrated the power model of the LTE network. Compared to 3G, LTE provides the promise of higher energy efficiency as a result of a new resource management policy and higher achievable throughput. However, this new technology has not been extensively studied empirically in a deployed commercial network setting to understand how network resources are utilized across different protocol layers for real users. It is important to evaluate the benefits of increased bandwidth for popular mobile applications and essential network protocols to identify their limitations for needed improvements. Intuitively, network protocol overheads can be significant enough to prevent efficient usage of available network resources [2]. Also, exploiting LTE as an access network technology for IoT applications is an opportunity to be considered by telecom and service operators, due to its pervasive diffusion and the advantages it brings.

RATIONALE:

The IoT is considered as one of the disruptive technology directions in future mobile communication standards, and it is forecast that around 7 billion connected devices will be deployed over cellular networks by 2025. The novelty of the IoT is not in the functional capability of a smart object (already today many embedded systems are connected to the Internet) but in the expected size of billions or even trillions of smart objects that bring about novel technical and societal issues that are related to size. Some examples of these issues are: authentic identification of a smart object, autonomic management and self-organization of networks of smart objects, diagnostics and maintenance, context awareness and goal-oriented behavior, and intrusion of the privacy. Special attention must be given to smart objects that can act in the physical world and can physically endanger people and their environment.

By considering seamless coverage, bandwidth, security, delay, throughput and reliability requirements of connecting industrial appliances with confidential and mission critical applications, we strongly believe that LTE is one of the most suitable wireless connectivity technologies for such applications. In particular, LTE offers secure end-to-end wireless broadband service to mobile user equipment with well-defined quality-of-service requirements. The recently opening up of 3.65 GHz CBS band can in fact be utilized for deploying private LTE small-cell networks for connecting industrial appliances directly to a desired network without intermediate agents if one ensures proper interfacing between appliances and LTE UE.

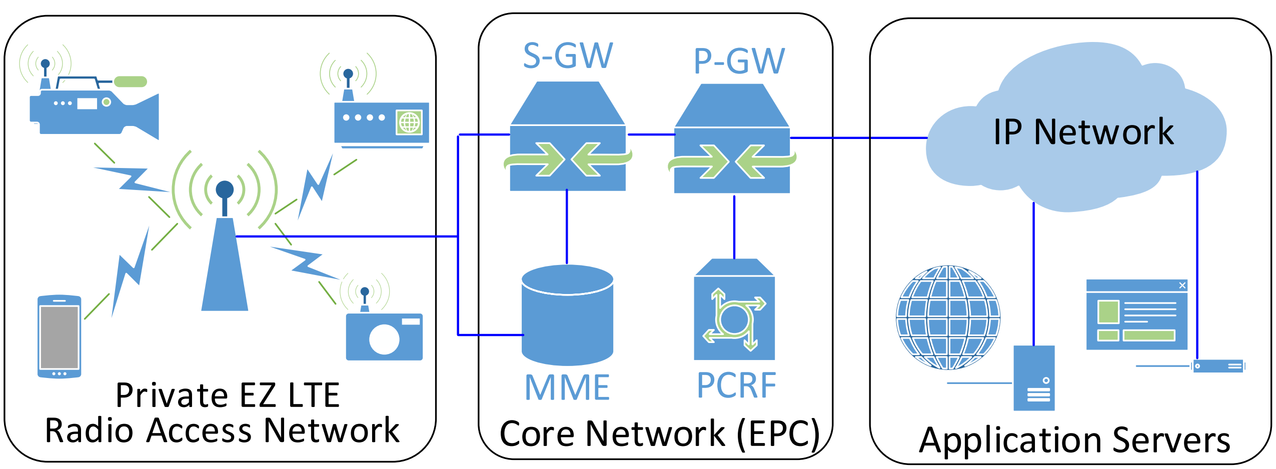
CURRENT SOLUTION:

In industrial settings, most of the appliances are controlled and monitored by connecting them to the data fusion centers through (i) proprietary wireless or wired connections, (ii) contention-based WiFi, and (iii) ZigBee wireless networks. The application servers which are used to control and monitor industrial appliances are either connected to local network or to the outside IP network. Prior efforts [3][4][5] deployed smartphone user studies and collected data from tens to hundreds of participating users. Those studies investigated various aspects including the diversity of smartphone users, the popularity of mobile applications, and the effectiveness of compression techniques on cellular traffic.

INADEQUACY:

The aforementioned current solution can be highly unsecure as well as unreliable for certain industrial settings with confidential and mission critical applications. Further, the scalability of proprietary wireless and wired connections can be expensive and in some cases a very few appliances can be controlled or monitored simultaneously. WiFi is mainly designed for wireless local area networks with limited coverage areas. WiFi can be inappropriate for confidential and mission critical industrial applications as it adopts carrier sense for wireless channel access, resulting in a limited support for QoS control and unreliable\unsecure connections. Moreover, ZigBee has very small coverage areas and can be significantly unreliable/unsecure in industrial settings.

PROPOSED SOLUTION:



We are motivated by the fact that LTE uses unique backhaul and radio network technologies, and has unique features distinguishing it from other access technologies (e.g., much higher available bandwidth and lower RTT), requiring some existing topics to be revisited. Also, the prevalence of these problems in commercial LTE networks is very important for both academia and industry. In this project, we focus on characterizing the usage of a private LTE network starts with a careful analysis of basic network characteristics in terms of flow properties, network latency, followed by the congestion control statistics of observed network flows. Also, we will study and report the preliminary results of an analysis of the suitability of LTE as the wireless technology to connect IoT gateways to the Internet.

Additionally, we propose methodologies for interfacing, controlling and monitoring IoT devices in industrial settings over private LTE small-cell networks over 3.65 GHz frequency band. In order to provide network security, various industrial appliances need to be interfaced directly to the LTE user equipment (UE) without intermediate agents. To this end, LTE UE must support variance appliance interfaces. To this end, this project will focus on the integration of LTE small-cell networks to industrial appliances (e.g. fluid control valves/actuators) with LTE UE over 3.65 GHz supporting standard industry interfaces. Thereby, we aim to characterize and optimize the performance of such industrial appliances over the private LTE network. Specifically, this project will focus on enabling data management for connected objects and back-end infrastructure by developing and providing server side software and end point components under private LTE network. The server will provide all the back-end functionality needed to operate large-scale and mission-critical IoT solutions. It will handle all the communication across connected objects, including data consistency and security, device interoperability, and failure-proof connectivity. The server will also offer well-established interfaces for integration with data management and analytics systems, as well as with any product-specific services. The developed services include but are not limited to: (i) Building device inventory; (ii) Capturing, grouping and managing devices; (iii) Performing device provisioning and configuration; (iv) Enabling cross-device communication; (v) Performing real-time device monitoring by collecting and analyzing data; (vi) Delivering notifications; and (vii) Distributing firmware updates. In order to expand the utilization and connectivity properties of the private LTE network, focus will be given on developing device specific drivers, for private LTE network, that will allow the support of multiple user-end devices.

NOVELTY:

This project:

- Will report the preliminary results of an analysis of the suitability of LTE as the wireless technology to connect IoT gateways to the Internet.
- Will characterize the usage of a commercial LTE network starts with a careful analysis of basic network characteristics in terms of flow properties
- Will validate the accuracy of bandwidth estimation algorithms using controlled experiments
- Given the prevalence of video and audio applications in cellular networks and their significant contribution to the network resource usage, the project will perform a case study on popular multimedia applications from the perspectives of network resource usage.
- Based on these observations, we make several recommendations on protocol and application design to more effectively take advantage of the available network resources.

POTENTIAL BENEFITS TO INDUSTRY MEMBERS:

The developed framework for supporting Internet-of-Things applications will be useful in many situations for the member companies. Firstly, new techniques for characterizing the usage of a private LTE network starts will be evaluated. Also, user-end applications will be integrated and tested. Last, device specific drivers will allow the support of new devices in the private LTE network.

DELIVERABLES:

The proposed project deliverables will be as follows:

1. Comprehensive report on the developed techniques and network utilization. The report will also include the results regarding application and system requirements.
2. A demo of a simple IoT scenario: Couple of nodes acting as actuators communicating with the server under the private LTE network.

TIMELINE / MILESTONES (PER QUARTER):

Quarter 1: Study of existing IoT tools and network utilization methodologies-algorithms.
Quarter 2: Define software architecture and hardware specifications for IoT applications.
Quarter 3: Development of the aforementioned IoT framework. First ideas about demo functionality.
Quarter 4: Finalize development, demo and report.

TECHNOLOGY TRANSFER:

Technology transfer will be performed in the form of comprehensive reports regarding the developed IoT applications and the device specific drivers.

BUDGET:

The requested budget is $35,000. The budget will cover travel expenses for meetings and student salaries. $15,000 will be used for acquiring the necessary equipment.

BIBLIOGRAPHY: (ATTACH IN IEEE CONFERENCE OR JOURNAL FORMAT)

[1] J. Huang, F. Qian, A. Gerber, Z. M. Mao, S. Sen, and O. Spatscheck. A Close Examination of Performance and Power Characteristics of 4G LTE Networks. In MobiSys, 2012.

[2] Z. Zhuang, T.-Y. Chang, R. Sivakumar, and A. Velayutham. A3: Application-Aware Acceleration for Wireless Data Networks. In MOBICOM, 2006.

[3] H. Falaki, R. Mahajan, S. Kandula, D. Lymberopoulos, and R. G. D. Estrin. Diversity in Smartphone Usage. In MobiSys, 2010.

[4] C. Shepard, A. Rahmati, C. Tossell, L. Zhong, and P. Kortum. LiveLab: Measuring Wireless Networks and Smartphone Users in the Field. In HotMetrics, 2010

[5] F. Qian, J. Huang, J. Erman, Z. M. Mao, S. Sen, and O. Spatscheck. How to Reduce Smartphone Traffic Volume by 30%? In PAM, 2013.

BIOGRAPHICAL SKETCH

Iraklis Anagnostopoulos

Electrical and Computer Engineering Department

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Professional Preparation:

- National Technical University of Athens, Greece, Athens, Greece
  Electrical Engineering B.S. 2008
- National Technical University of Athens, Greece, Athens, Greece
  Electrical Engineering Ph.D. 2014

Appointments:

- Assistant Professor, ECE Department of Southern Illinois University, Carbondale, 2015-present
- Post-doc, ECE Department of National Technical University of Athens, 2014-2015
- Graduate Research Assistant, ECE Department of National Technical University of Athens, 2008-2014

Publications Most Closely Related to the Proposed Project:

- I. Anagnostopoulos, J.M. Chabloz, I. Koutras, A. Bartzas, A. Hemani, D. Soudris, “Power-aware Dynamic Memory Management on May-core Platforms utilizing DVFS,” *ACM Transactions on Embedded Computing Systems*, vol.13, no.1, pp.40:1–40:25, November 2013.
- K. Gyftakis, I. Anagnostopoulos, D. Soudris and D. Reisis, "A MapReduce framework implementation for Network-on-Chip platforms", *21st IEEE International Conference on Electronics, Circuits, and Systems,* Marseille France, December 2014.
- I. Anagnostopoulos, V. Tsoutsouras, A. Bartzas, D. Soudris, “Distributed run-time resource management for malleable applications on many-core platforms,” *in Proceedings of DAC conference* 2013.
- I. Anagnostopoulos, A. Bartzas, G. Kathareios, D. Soudris, “A Divide and Conquer based Distributed Run-time Mapping Methodology for Many-Core platforms,” *in Proceedings of DATE conference* 2012.

Other Significant Publications:

- B. Candaele, D. Soudris, I. Anagnostopoulos, “Trusted Computing for Embedded Systems,” *ISBN 978-3-319-09420-5, Springer*, 2014.
- I. Anagnostopoulos, A. Bartzas, I. Filippopoulos, D. Soudris, “High-level Customization Methodology for Application-Specific NoC Architectures,” *Springer Design Automation for Embedded Systems,* vol.16, no.4, pp.339-361, 2013, doi: 10.1007/s10617-013-9114-5.
- I. Anagnostopoulos, S. Xydis, A. Bartzas, Z. Lu, D. Soudris, A. Jantsch, “Custom Microcoded Dynamic Memory Management for Distributed On-Chip Memory Organizations,” *IEEE Embedded System Letters*, 2011.

- A. Bartzas, P. Bellasi, I. Anagnostopoulos, C. Silvano, W. Fornaciari, D. Soudris, D. Melpignano, C. Ykman-Couvreur, “Runtime Resource Management Techniques for Many-core Architectures: The 2PARMA Approach,” in *Proceedings of the International Conference on Engineering of Reconfigurable Systems and Algorithms (ERSA*), 2011.
- S. Xydis, A. Bartzas, I. Anagnostopoulos, D. Soudris, K. Pekmestzi, “Custom Multi-Threaded Dynamic Memory Management for Multiprocessor System-on-Chip Platforms,” *in Proceedings of International Conference on Embedded Computer Systems: Architectures, Modeling, and Simulation (SAMOS)* 2010.

Synergistic Activities:

- Director of Embedded Systems Software lab in SIUC
- Program Committee: SAMOS conference 2015
- HiPEAC Paper Award: Design Automation Conference, Austin, Texas, 2013
- Reviewer of IEEE Trans. On Computers, IEEE Micro, ACM Trans. On Embedded Systems, Journal of Low Power Electronics, Journal of Circuits, Systems and Computers, Elsevier Microprocessors and Microsystems

Collaborators and Other Affiliations:

- **Collaborators and Co-Editors:** Alexandros Bartzas (National Technical University of Athens, Greece), Bernard Candaele (Thales Group, France), Jean-Michel Chabloz (Royal Institute of Technology, Sweden), George Economakos (National Technical University of Athens, Greece), William Fornaciari (Polytechnic University of Milan, Italy), Ahmed Hemani (Royal Institute of Technology, Sweden), Axel Jantsch (Royal Institute of Technology, Sweden), Zhonghai Lu (Royal Institute of Technology, Sweden), Kiamal Pekmestzi (National Technical University of Athens, Greece), Dionysios Reisis (University of Athens, Greece), Chistina Silvano (Polytechnic University of Milan, Italy), Kostas Siozios (National Technical University of Athens, Greece), Dimitrios Soudris (National Technical University of Athens, Greece), Vasileios Tsoutsouras (National Technical University of Athens, Greece), Sotirios Xydis (National Technical University of Athens, Greece)
- **Thesis Advisor and Postgraduate-Scholar Sponsor:** Michael Weber, Setareh Behroozi, Giannis Galanis all at Southern Illinois University Carbondale

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Professional Preparation:

- University of Moratuwa, Sri Lanka, Department of Electronics and Telecommunications, B.Sc. in Engineering (Hons.), 2006
- University of Alberta, Edmonton, Alberta, Canada, Department of Electrical and Computer Engineering, Ph.D., 2013

Appointments:

- [Jan. 2016 - present] Assistant Professor, Department of Electrical and Computer Engineering, Southern Illinois University, Carbondale, IL
- [Jan. 2016 - present] Visiting Research Scholar, Department of Electrical Engineering, Princeton University, Princeton, NJ
- [Feb. 2014 - Jan. 2016] Postdoctoral Research Fellow, Department of Electrical Engineering, Princeton University, Princeton, NJ
- [Nov. 2006 - Jul. 2008] Wireless network planning engineer, Dialog Broadband Networks, Colombo, Sri Lanka

Five Related Publications:

- **G. Amarasuriya**, E. Larsson, H. Vincent Poor, ''Wireless Energy Harvesting and Information Transfer for Massive MIMO Relay Networks,'' accepted to IEEE Transactions on Wireless Communications, Feb. 2016.
- **G. Amarasuriya**, C. Tellambura and M. Ardakani, ''Sum Rate Analysis of Two-Way MIMO AF Relay Networks with Zero-Forcing,'' IEEE Transactions on Wireless Communications, vol. 12, no. 9, pp. 4456-4469, Dec. 2013.
- **G. Amarasuriya**, C. Tellambura and M. Ardakani, ''Multi-Way MIMO Amplify-and-Forward Relay Networks with Zero-Forcing Transmission,'' IEEE Transactions on Communications, vol. 61, no. 12, pp. 4847-4863, Dec. 2013.
- **G. Amarasuriya**, C. Tellambura and M. Ardakani, "Two-way Amplify-and-Forward Multiple-Input Multiple-Output Relay Networks with Antenna Selection,'' *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 8, pp. 1513-1529, Sep. 2012.
- **G. Amarasuriya**, C. Tellambura and M. Ardakani, ''Performance Analysis of Hop-by-hop Beamforming for Dual-Hop MIMO AF Relay Networks,'' *IEEE Transaction on Communications*, vol. 60, no. 7, pp. 1823-1837, Jul. 2012.

Five Other Significant Publications:

- S. De Silva**, G. Amarasuriya**, C. Tellambura, M. Ardakani, ''Relay Selection Strategies for Two-Way Relay Networks with Relay Selection,'' IEEE Transactions on Communications, vol. 63, no. 12, pp. 4694-4710, Dec. 2015.
- **G. Amarasuriya**, C. Tellambura and M. Ardakani, ''Joint Relay and Antenna Selection for Dual-hop Amplify-and-Forward MIMO Relay Networks,'' *IEEE Transactions on Wireless Communications*, vol. 11, no. 2, pp. 493-499, Feb. 2012.
- **G. Amarasuriya**, C. Tellambura and M. Ardakani, ''Performance Analysis Framework for Transmit Antenna Selection Strategies of Cooperative MIMO AF Relay Networks,'' *IEEE Transaction on Vehicular Technology*, vol. 60, no. 7, pp. 3030-3044, Sep. 2011.
- **G. Amarasuriya**, C. Tellambura and M. Ardakani, ''Asymptotically-Exact Performance Bounds of AF Multi-Hop Relaying over Nakagami Fading,'' *IEEE Transaction on Communication*, vol. 59, no. 4, pp. 962-967, Apr. 2011.
- **G. Amarasuriya**, M. Ardakani and C. Tellambura, ''Output-Threshold Multiple-Relay-Selection Scheme for Cooperative Wireless Networks,'' *IEEE Transaction on Vehicular Technology*, vol. 59, no. 6, pp. 3091-3097, Jul. 2010.

Synergistic Activities:

- Recipient of NSERC PDF award, Natural Sciences and Engineering Research Council of Canada (Ranked 2nd in Electrical Engineering Committee in the Canada-wide competition - 2014) [Feb. 2014 – Jan. 2016]
- Recipient of the best paper award in wireless communications symposium, IEEE Global Communications Conference 2015, San-Diego, USA.
- Recipient of Izaak Walton Killam Memorial Scholarship, the most prestigious graduate student award in University of Alberta [May 2012 – Apr. 2014]
- IEEE Exemplary Reviewer [three consecutive years – 2011-2013]
- Member of the editorial board - Jacobs Journal of Electronics and Communications [Mar. 2016 - present]
- Recipient of the Andrew Stewart Memorial Graduate Prize for an exemplary research contribution during the Ph.D. degree, University of Alberta, Canada, 2012.
- Recipient of the AITF Ph.D. Graduate Student Scholarship in ICT, Alberta Innovates Technology Future, Alberta, Canada [May 2010 – Apr. 2012]
- Technical program committee member, IEEE international Conferences
- Technical reviewer, IEEE Transactions and Journals

Ph.D. Thesis Advisors: Chintha Tellambura and Masoud Ardakani (University of Alberta, Canada)

Postdoctoral research Advisor: H. Vincent Poor (Princeton University)

Collaborators: H. Vincent Poor (Princeton University, NJ, USA), Erik Larsson (Linköping University, Sweden), Chnitha Tellambura (University of Alberta, Canada), Masoud Ardakani (University of Alberta, Canada), Rafael Schaefer (Technische Universität Berlin)

Graduate student supervisions: Dhanushka Kudathanthirige (Ph.D.) and Hayder Al-Hraishawi (Ph.D.)

I/UCRC Executive Summary - Project Synopsis		Date:
Project Title: Internet-of-Things Applications Development for Private LTE Small-Cell Networks		
Center/Site: Center for Embedded Systems/Southern Illinois University Carbondale		
Principle Investigator: Iraklis Anagnostopulos, Gayan Aruma Badgue		**Type: (New or Continuing)** New
Tracking No.: (CES office to input)	**Phone :** (618) 453-7034	**E-mail:** iraklis.anagno@siu.edu, gayan.baduge@siu.edu
		Proposed Budget: $35,000

Abstract: We are witnessing the dawn of a new era of Internet of Things (IoT). Generally speaking, IoT refers to the networked interconnection of everyday objects, which are often equipped with ubiquitous intelligence. Projections say that by the year 2020, 16 billion dynamic-networked devices will be deployed, and interact with the real world simultaneously generating huge quantities of data. This bloom of dynamic networked devices was also a result of new network services. With lower latency and higher bandwidth than its predecessor 3G networks, the latest cellular technology 4G LTE has been attracting many new users. However, the interactions among applications and network transport protocol still remain unexplored. In this project, we propose methodologies for interfacing, controlling and monitoring IoT devices in industrial settings over private LTE small-cell networks over 3.65 GHz frequency band.

Problem: The value of dynamic networked real-time systems is hidden in the increased value of information created by the number of interconnections and the transformation of the processed information into knowledge. However, the growing complexity of these systems, due to the high number of interconnected components and complex iterations among devices, will be unmanageable, and will obstruct the development of new services and applications. 4G LTE is the latest deployed cellular network technology that provides high-speed data services for mobile devices with advertised bandwidths matching and even exceeding the home broad band network speeds. However, this new technology has not been extensively studied empirically in a deployed commercial network setting to understand how network resources are utilized across different protocol layers for real users. It is important to evaluate the benefits of increased bandwidth for popular mobile applications and essential network protocols to identify their limitations for needed improvements.

Rationale / Approach: The recently opening up of 3.65 GHz CBS band can in fact be utilized for deploying private LTE small-cell networks for connecting industrial appliances directly to a desired network without intermediate agents if one ensures proper interfacing between appliances and LTE UE. In this project, we focus on characterizing the usage of a private LTE network stats with a careful analysis of basic network characteristics in terms of flow properties, network latency, followed by the congestion control statistics of observed network flows. Also, we will study and report the preliminary results of an analysis of the suitability of LTE as the wireless technology to connect IoT gateways to the Internet. Additionally, we will propose methodologies for interfacing, controlling and monitoring IoT devices in industrial settings over private LTE small-cell networks over 3.65 GHz frequency band. Last, in order to expand the utilization and connectivity properties of the private LTE network, focus will be given on developing device specific drivers, for private LTE network, that will allow the support of multiple user-end devices.

Novelty: This project: (i) will study and analyze LTE as the wireless technology to connect IoT gateways to the Internet; (ii) Will characterize the usage of a commercial LTE network; (iii) Will validate the accuracy of bandwidth estimation algorithms using controlled experiments; (iv) will perform a case study on popular multimedia applications from the perspectives of network resource usage; (v) will make several recommendations on protocol and application design to more effectively take advantage of the available network resources.

Potential Member Company Benefits: The developed framework for supporting Internet-of-Things applications will be useful in many situations for the member companies. Firstly, new techniques for characterizing the usage of a private LTE network starts will be evaluated. Also, user-end applications will be integrated and tested. Last, device specific drivers will allow the support of new devices in the private LTE network.

Deliverables for the proposed year: The proposed project deliverables will be as follows: (i) Comprehensive report on the developed techniques and network utilization. The report will also include the results regarding application and system requirements; and (ii) a demo of a simple IoT scenario

Milestones for the proposed year: Q1: Study of existing IoT tools and network utilization methodologies-algorithms. Q2: Define software architecture and hardware specifications for IoT applications. Q3: Development of the aforementioned IoT framework. First ideas about demo functionality. Q4: Finalize development, demo and report.

Progress to Date: THIS SECTION TO BE UPDATED IN JANUARY

Estimated Start Date: 08/01/2016	**Estimated Knowledge Transfer Date**: 08/31/2017