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

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

TITLE:	Supporting Smart Machine Communication with Private LTE Network				
PI:	Kang Chen Gayan Aruma Badgue	**EMAIL:**	kchen@siu.edu gayan.baduge@siu.edu	**TEL:**	618-453-7038
DEPT:	ECE	**SCHOOL:**	SIU		

ABSTRACT: (250 or fewer words)

Smart industry machines and vehicles rely on the underlying network support for collaborative and intelligent manufacturing. To this end, LTE network presents several advantages over 802.11 WLAN such as security, high throughput, and quality-of-service (QoS) support. However, existing LTE networks and channels are only operated by commercial carriers, while industrial entities may wish to have a full control of the wireless network infrastructure. Those factors make private LTE network (in 3.65 GHz CBS brand) a suitable player in this field. Therefore, we propose to study the private LTE network's capability on supporting smart machine communication in terms of coverage, delay, reliability, and throughput. Both theoretical analysis and field measurement will be utilized in this process. We also plan to solve challenges identified in the first step through protocol design, application adaptation, and network structure innovation. The expected outcome of this research include the measurement results of key network performances, an initial framework for integrating private LTE network into the smart machine domain, as well as a few demonstration application examples.

PROBLEM:

Smart machines and vehicles need to communicate with one other (Machine-to-Machine) or to a certain server (Machine-to-Infrastructure) to complete various manufacturing tasks intelligently and collaboratively. Consider the vast amount of application scenarios, such a data communication proposes diverse requirements on the underlying wireless networks including security, mobility, bandwidth, reliability, and QoS. For example, key synchronization messages need to be delivered timely within a guaranteed amount of delay. Certain manufacturing scenarios need mobile broadband for the transfer of high-definition videos. For commercial interests, data transmitted over the wireless network needs to be protected against eavesdropping or intrusion in certain scenarios. Furthermore, companies would like to operate on their own wireless communication infrastructures for more effective management and control. Those facts raise an important question about how to design a suitable wireless network that can better satisfy aforementioned requirements. Therefore, in this research, we study whether private LTE network on the 3.65 GHz CBS band can well serve this purpose.

RATIONALE:

After examining existing wireless network technologies, we observe LTE to be a suitable wireless network technology for smart machine communication. This is majorally because LTE can offer secure wireless broadband service to mobile clients with well-defined QoS support. However, current LTE networks and corresponding frequency bands are all owned and operated by carriers, which prevents manufactures from building their own wireless communication infrastructures. The recently opening up of 3.65 GHz CBS band removes the barriers on building private LTE networks for smart machines. However, private LTE network cannot satisfy all requirements of smart machines naturally. First, the 3.65 GHz CBS band is shared across geographical locations rather than being exclusively owned by a user. This makes private LTE suffers from limited coverage and mobility support. In

addition, when LTE network is adopted, machine-to-machine communication is relayed through the LTE base-station. This may suffer from scalability issues when the number of machines increases. Those issues may degrade the efficiency of smart machine communications. As a result, it is meaningful to understand whether smart machine communication is an appropriate application domain of private LTE network.

CURRENT SOLUTION:

Existing major radio access technologies include WiFi, WiMAX, and LTE. WiFi is the representative technology for wireless local area network, while WiMAX and LTE are representative technologies for mobile broadband service in a broad area. Furthermore, WiFi is designed on the unlicensed frequency (e.g., 2.4 GHz ad 5.0 GHz), while WiMAX and LTE are designed on licensed frequency. This means that unless a WiMAX/LTE band becomes publicly available, it is impossible to build a private WiMAX/LTE network. Fortunately, the opening up of CBS frequency band makes this problem no longer a barrier.

INADEQUACY:

WiFi is mainly designed for local area usage scenarios. Therefore, it has a small coverage with a poor mobility support. For simplicity, WiFi adopts carrier sense for wireless channel access, resulting in a limited support for QoS control. Furthermore, WiFi suffers from security concerns. Those factors make WiFi inappropriate for industry machine and vehicle scenarios. On the contrary, both WiMAX and LTE are mobile broadband technology that offers wireless data communication in a wide area with well supported QoS and security. This indicates that both technologies are suitable candidates. However, we prefer LTE as it now becomes the dominant technology in 4G and is on the evolution map towards future 5G technology. Therefore, adopting LTE can better protect the investment on those infrastructures under technology upgrade.

PROPOSED SOLUTION:

In this research, we investigate new system models/designs, develop new algorithms for smart connectivity, and evaluate the performance of the proposed solutions through field measurements and analytical tools for the private LTE networks (on the CBS band) in supporting industry smart machines and vehicles. The proposed research includes three key technology directions; (i) measurement study, (ii) theoretical analysis, and (iii) performance enhancement through algorithm/system design. We introduce the details in the following.

Measurement Study

In this step, we plan to measure the following performance metrics of private LTE network in both machine to machine and machine to infrastructure communication.

- **Delay**: the distribution of packet delays in both crowd and sparse scenarios.
- **Throughput**: the throughput a machine can achieve in both crowd and sparse scenarios.
- **QoS support**: measure the delay of and throughput of nodes under different QoS configurations. This measurement tries to answer what guarantee can the private LTE network offer?
- **Handoff under mobility**: measure the delay, throughput, and packet loss probability when a machine moves from one base station to another base station.

Theoretical Analysis

In this step, we will conduct theoretical analysis to validate the results of the first step. It can also help us better understand the performance of the private LTE network. Further, these analytical tools will be used to optimized the proposed designs and algorithms, and thereby, refining the final solution. The theoretical analysis will supplement the field measurements and will also be used to justify the performance of the proposed solutions.

Performance Enhancement

With the data measured through the first step, we plan to identify a few challenges and propose solutions through algorithm design and network structure innovation. To achieve this goal, we will first identify a few representative industry application scenarios and understand their needs on the underlying network. For example, the mining vehicles in a mining field. We then compare application requirements with measured performance metrics to identify the gaps. After this, we will design novel algorithms to bridge or alleviate the gap. One potential work we can foresee is to guarantee the packet delivery probability under the handoff scenario, i.e., prevent packet loss as much as possible. This problem is caused by the shifting of the packet anchor point from one base station to another during the handoff. The potential solution for this problem can be creating additional caches at either the client side or the base station, when a handoff is predicted to happen.

NOVETY:

The novelty of this project lies in the investigation of a new application domain of a mature 4G wireless communication technology (i.e. LTE) under the CBS frequency band. It can be regarded as a pilot project of extending private LTE to the smart machine domain upon the opening up of the CBS frequency band. Therefore, the proposed algorithms, designs, analytical performance analysis tools, and optimization techniques for smart connectivity in industrial machines and vehicles will be unique for private LTE networks operating over the newly released CBS band.

POTENTIAL BENEFITS TO INDUSTRY MEMBERS:

With the results from this research project, industry members can better evaluate whether private LTE network fits into their smart manufacturing/production environment. For companies with traditional machines, this project can also promote the transition of importing smart machines.

DELIVERABLES:

The deliverables of this project include a technical report and the code implementation of proposed enhancement algorithms. The report summarizes all findings and theoretical analysis obtained from the project. For example, it will include the distributions of delays and throughputs in various scenarios, as well as the theoretical analysis that supports the measurement results. Such a report can offer a better understanding of the capability of private LTE network in the smart machine domain.

TIMELINE / MILESTONES (PER QUARTER):

Quarter 1: Study the existing wireless connectivity techniques in industry smart machines and vehicles technologies.
Quarter 2: Design algorithms and designs for smart connectivity by using private LTE networks in the CBS band.
Quarter 3: Develop analytical tools for evaluating and optimizing the proposed designs and algorithms
Quarter 4: Validate, optimize and finalize the proposed solutions by using field measurements, trials and integration.

TECHNOLOGY TRANSFER:

The proposed algorithms, designs, performance analysis tools, and optimization techniques for smart connectivity in private LTE networks will directly be related to the interests and priorities of Lemko, and the corresponding technology transfer will be performed in the form of regular meetings, comprehensive reports, software packages, and prototype devices.

BUDGET:

The requested budget is $30,000. $10,000 will be used for acquiring the necessary equipment. The remaining $20,000 will cover the travel expenses for meetings and student salaries.

Biographical Sketch

Kang Chen, Ph.D.

http://mypage.siu.edu/kchen/

Professional Preparation

- [B.E. 2005] Huazhong University of Science and Technology, Wuhan, China, Electronics and Information Engineering
- [M.S. 2008] Graduate University of Chines Academy of Sciences, Beijing, China, Telecommunication and Information System
- [Ph.D. 2014] Clemson University, Clemson, SC, Computer Engineering

Appointments

- Assistant Professor, Department of Electrical and Computer Engineering, Southern Illinois University Carbondale, August 2015 – present
- Postdoctoral Research Fellow, Department of Electrical and Computer Engineering, Clemson University, August 2014 – July 2015

Related Products (Chronological)

1. **Kang Chen**, Jianwei Liu, James Martin, Kuang-Ching Wang, and Hongxin Hu, Exploiting SDN for Efficient Flow Scheduling in Integrated LTE-WiFi Network, submitted to *IEEE International Conference on Distributed Computing Systems (ICDCS)*, 2016
2. **Kang Chen**, Ryan Izard, Hongxin Hu, Kuang-Ching Wang, Target-Oriented Low-Delay Node Searching in DTNs with Social Network Properties, James Martin, and Juan Deng, SDN based Intelligent Network Access in Heterogeneous Wireless Networks, submitted to *International Workshop on Software-Driven Flexible and Agile Networking (SWFAN)*, 2016
3. Bo Wu, Haiying Shen, and **Kang Chen**, DIAL: A Distributed Adaptive-Learning Routing Method in VDTNs, in *Proc. of the 1st IEEE International Conference on Internet-of-Things Design and Implementation (IoTDI)*, 2016
4. **Kang Chen** and Haiying Shen, Fine-grained Encountering Information Collection under Neighbor Anonymity in Mobile Opportunistic Social Networks, *Proc. of the 23rd IEEE International Conference on Network Protocols (ICNP)*, 2015
5. **Kang Chen** and Haiying Shen, DTN-FLOW: Inter-landmark Data Flow for High-throughput Routing in DTNs, *IEEE/ACM Transactions on Networking*, 23(1):212–226, 2015

Other Related Products (Chronological)

1. Li Yan, Haiying Shen and **Kang Chen**, , *Proc. of the 34th Annual IEEE International Conference on Computer Communications (INFOCOM)*, 2015
2. **Kang Chen** and Haiying Shen, Dsearching: Distributed Searching of Mobile Nodes in DTNs with Floating Mobility Information, *Proc. of the 33rd Annual IEEE International Conference on Computer Communications (INFOCOM)*, 2014
3. **Kang Chen**, Haiying Shen, and Haibo Zhang, Leveraging Social Networks for P2P Content-based File Sharing in Disconnected MANETs, *IEEE Transactions on Mobile Computing*, 13(2):235–249, 2014
4. **Kang Chen** and Haiying Shen, SMART: Lightweight Distributed Social Map based Routing in Delay Tolerant Networks, *Proc. of the 20th IEEE International Conference on Network Protocols (ICNP)*, 2012
5. **Kang Chen** and Haiying Shen, Global Optimization of File Availability through Replication for Efficient File Sharing in MANETs, *Proc. of the 19th IEEE International Conference on Network Protocols (ICNP)*, 2011.

Synergistic Activities

- Supported the organization of the connected vehicle research group at Clemson University.
- Served as the technical program committee for several conferences including ICCCN'2015'2016, ICPP'2015, IWCMC'2015, and NAS'2015.
- Served as the reviewer for IEEE transactions including IEEE Transactions on Mobile Computing, IEEE Transactions on Parallel and Distributed Systems, IEEE Transactions on Computers, IEEE Transactions on Intelligent Transportation Systems.

Collaborators (10 listed)

- Iraklis Anagnostopoulos (SIU), Richard R. Brooks (Clemson), Mashrur Chowdhury (Clemson), Hongxin Hu (Clemson), Yaoqing Liu (Clarkson), Chao Lu (SIU), Jim Martin (Clemson), Haiying Shen (Clemson), Kuang-Ching Wang (Clemson), Ning Weng (SIU),

Graduate Advisor and Postdoctoral Sponsor (2 listed)

- Prof. Haiying Shen (Clemson University), Prof. Kuang-Ching Wang (Clemson University)

Thesis Advisor and Postgraduate-Scholar Sponsor (2 listed)

- Bhargava Katrepalli (PhD, SIU), Baraa Saeed Ali (PhD, SIU), Mijanur Rahaman Palash (MS, SIU)

Gayan Amarasuriya Aruma Baduge

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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.)

PI INFORMATION: (ATTACH 2-PAGE CV):

I/UCRC Executive Summary - Project Synopsis		**Date:**
Project Title: Supporting Smart Machine Communication with Private LTE Network		
Center/Site: Center for Embedded Systems (CES)/SIU		
Principle Investigators: Kang Chen and Gayan Aruma Baduge		**Type: (New or Continuing)** New
Tracking No.: (CES office to input)	**Phone :** 618-453-7038	**E-mail :** (kchen, gayan.baduge)@siu.edu
		Proposed Budget: $30000

Abstract: (250 words max) Smart industry machines and vehicles rely on the underlying network support for collaborative and intelligent manufacturing. To this end, LTE network presents several advantages over 802.11 WLAN such as security, high throughput, and quality-of-service support. However, the existing LTE networks and channels are only operated by commercial carriers, while industrial entities may wish to have a full control of the wireless network infrastructure. To this end, we propose to study the private LTE network's capability on supporting smart machine communication in terms of coverage, delay, reliability, and throughput. Thereby, we aim to propose algorithms, system designs, application adaptation techniques, network structure innovation and optimization techniques for enhancing the performance of smart connectivity by using both theoretical analysis and field measurement. The expected outcome of this research include the measurement results of key network performances, an initial framework for integrating private LTE network into the smart machine domain, as well as a few demonstration application examples.

Problem: Smart machines and vehicles need to communicate in either machine-to-machine or machine-to-infrastructure manner to complete various manufacturing tasks intelligently and collaboratively. The vast amount of applications of such data communications imposes diverse requirements on the underlying wireless networks including security, mobility, bandwidth, reliability, and QoS. Thus, it is indispensable to design a suitable wireless network that can better satisfy the aforementioned requirements. Therefore, in this research, we study whether private LTE network on the 3.65 GHz CBS band can well serve this purpose.

Rationale / Approach: LTE is most suited for smart machine communication as they provide secure wireless connectivity with well-defined QoS support. However, current LTE networks and corresponding frequency bands are all owned and operated by carriers, which prevents the deployment of private wireless infrastructure. The recently released 3.65 GHz CBS band can be exploited to circumvent such barriers.

Novelty: The novelty of this project lies in the investigation of a new application domain of a mature 4G wireless communication technology (i.e. LTE) under the CBS frequency band. Therefore, the proposed algorithms, designs, analytical performance analysis tools, and optimization techniques for smart connectivity in industrial machines and vehicles will be unique for private LTE networks operating over the newly released CBS band.

Potential Member Company Benefits: With the results from this research project, industry members can better evaluate whether private LTE network fits into their smart manufacturing/production environment. For companies with traditional machines, this project can also promote the transition of importing smart machines.

Deliverables for the proposed year: (i) Technical report, (ii) Software implementation, (iii) prototype design The report summarizes all proposed designs, algorithms, optimization techniques, and theoretical analysis obtained from the project. The software implementations include code packages and prototype design include the proposed solution

Milestones for the proposed year: Quarter 1: Review the existing wireless connectivity techniques in industry smart machines and vehicles technologies. Quarter 2: Design algorithms and designs for smart connectivity by using private LTE networks in the CBS band. Quarter 3: Develop analytical tools for evaluating and optimizing the proposed designs and algorithms Quarter 4: Validate, optimize and finalize the proposed solutions by using field measurements, trials and integration.

Progress to Date: **THIS SECTION TO BE UPDATED IN JANUARY**

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