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E-LETTER

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CONTENTS

Message from MMTC Chair

Dear MMTC colleagues:

It was a great pleasure for me to serve as the new Chair for for this vital ComSoc Committee during the period 2014-2016! At Sydney a new leadership team has been confirmed, including:

- Chair: Yonggang Wen, Singapore
- Steering Committee Chair: Luigi Atzori, Italy
- Vice Chair - North America: Khaled El-Maleh, USA
- Vice Chair – Asia: Liang Zhou, China
- Vice Chair - Europe: Maria G. Martini, UK
- Vice Chair - Letters: Shiwen Mao, USA
- Secretary: Fen Hou, China
- Standard Liaison: Zhu Li, USA

All new leaders have been contributing to MMTC for a few years and have had quite a lot experience in organizing events and leading initiatives under previous leadership teams.

MMTC, owing to the capable leaders during previous teams (e.g., Jianwei Huang and Haowei Hong), has become one of the most vibrant technical committees within IEEE Communication Society. We have instituted a SIG structure which has become the backbone to support all the technical activities. Other sister technical committees are starting to adopt our approach. Our unique profile of TC-level publications, including E-Letter and R-Letter, has attracted a lot of high-quality publications and its broader impact is evidenced by its H-index. Other successful initiatives are abundant in our MMTC.

In this new term (2014-2016), the new team pleadges to work to our best to increase the visability and influence of MMTC within IEEE ComSoc. We will work with the newly endorsed team to continue all the exisiting initatives and develop additional programs in response to the changing enviroments in IEEE and/or ComSoc. The new team is discussing our strategies over next two years and will firm out a list of action items within 2 months. At the same time, we always believe that bottom-up approaches could bring creatitivity to our volunteer organization. Moreover, we are welcome more volunteers to donate their time and efforts to lead our SIGs. Thefore, on behalf of the new team, I am sincere to seek your support, feedback and contribution in commenting on our existing programs and suggesting new programs. You can also email me (ygwen@ntu.edu.sg) and/or Dr. Fen Hou (fenhou@umac.edu).

Finally, I would like to thank all the existing IG chairs and other volunteers for the work they have already done and will be doing for the success of MMTC and hope that any of you will find the proper IG of interest to get involved in our community!

Yonggang Wen
Chair, Multimedia Communications TC of IEEE ComSoc

EMERGING TOPICS: SPECIAL ISSUE ON MACHINE-TO-MACHINE COMMUNICATIONS

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With an emergence of Internet of Things (IoT), the data communication plays a crucial role to connect thousands of devices to transfer data and support a variety of applications including multimedia. As a result, the concept of machine-to-machine (M2M) communication has been introduced to support data transfer among a number of wireless devices such as sensors and actuators. The important features of M2M communication are as follows: firstly, there are a number of devices, and secondly, data size is small (e.g., a few bytes). Therefore, the new channel access schemes based on random access instead of fixed allocation will be preferred. Moreover, new radio resource management has to be developed to meet special requirements of M2M communication and IoT applications.

This special issue of E-Letter focuses on the recent progresses of machine-to-machine (M2M) communications which can support multimedia communications. It is the great honor of the editorial team to have four leading contributors from academia to report their ideas/solutions for meeting the challenges and share their latest results.

The first letter by Germán, Čedomir, and Petar with the title "Reliable M2M Communications for a Massive Number of Devices with Reporting Deadlines" introduces a system with a pool of radio resources that are reserved for M2M communication. The resource pool is updated periodically and the updating period is chosen to meet a transmission deadline. The work considers more sophisticated case when there are multiple packets and the packet transmission can be in error. Under this circumstance, the work analyzes the number of M2M devices such that the reliability of data report can be achieved at a certain target. To be related to practical networks, the analysis is performed based on LTE systems.

In the second letter, titled "Channel-Hopping on Multiple Channels for Full Rendezvous Diversity in M2M Cognitive Networks" by Utku and Teng Joon, cognitive radio networks for M2M communication is considered. In the cognitive radio networks, Channel-hopping (CH) is used as a practical method for rendezvous for data transmission among secondary users. Intelligently designed CH sequences can guarantee rendezvous between secondary userss with finite time-to-rendezvous (TTR) as long as there is at least one common available channel. Therefore, the work focuses on the design of M-channel CH sequences. This will allow secondary users to establish data transmission on all common available channels in asynchronous environments. The proposed design does not require secondary users to have prior knowledge on channel states, and it can be applied efficiently for asymmetric systems. Furthermore, the work introduces an optimal CH sequence design attaining full rendezvous diversity in the shortest possible CH sequence period length.

The third letter, titled "Machine-to-Machine (M2M) Communications for Smart Grid" by Yan, Rong, and Stein presents the visions on a new M2M communications paradigm, i.e., Cognitive radio enabled M2M (CM2M). The authors highlight the potentials of this communication system in the smart grid application. The work first identifies the motivations in exploiting cognitive radio technology in M2M communications from different aspects, including technical, applications, industry support, and standardization perspectives. Then, a CM2M communications architecture for the smart grid is presented.

The fourth letter, titled "Coalition Formation for Heterogeneous Machine Type Communications", considers the M2M communication that devices can cooperate to relay data transmission of each other, reducing congestion in the network. The work formulates a coalition formation game to determine groups of M2M devices that will perform relay transmission for each other. Additionally, if the devices are in coverage areas of small-cells, the devices in a coalition can choose to transmit to the small-cell to achieve better performance due to local transmission. The stable coalitions, i.e., Nash-stable, are analyzed.

Dusit Niyato is currently an Associate Professor in the School of Computer Engineering, at the Nanyang Technological University, Singapore. He received Ph.D. in Electrical and Computer Engineering from the University of Manitoba, Canada in 2008. His research interests are in the area of the optimization of wireless communication and mobile cloud computing, smart grid systems, and green radio communications.

Reliable M2M Communications for a Massive Number of Devices with Reporting Deadlines

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1. Introduction

In this letter, we consider a system with a periodically occurring pool of resources that are reserved M2M communications and shared for uplink transmission by all M2M devices. The period is selected such that if a report is transmitted successfully within the upcoming resource pool, then the reporting deadline is met. If each reporting device has a deterministic number of packets to transmit in each resource pool and if there are no packet errors, then the problem is trivial, because a fixed number of resources can be pre-allocated periodically to each device. However, if the number of packets accumulated between two reporting instances is random and the probability of packet error is not zero, then the number of transmission resources required per device in each period is random. In this case, as the number of transmission resources in each instance of the resource pool is fixed, the following question arises: *How many periodically reporting devices can be supported with a desired reliability of report delivery (i.e., 99.99\%), for a given number of resources reserved for M2M communications?* We elaborate the proposed approach in LTE context; however, the presented ideas are generic and implementable in other systems.

2. System Model

We focus on the case of periodic reporting, where the length of the reporting interval (RI), denoted by T_{RI}, depends on the application requirements [1]. The M2M resources for uplink transmission are reserved to occur periodically, once within the RI. The periodic reporting is modeled as a Poisson process with arrival rate $\lambda = 1/T_{RI}$, where devices can actually send none, one, or multiple reports within RI [2]. We assume that all report arrivals that occur within the current reporting interval are served in the next reporting interval.

The organization of LTE uplink resources is given in Fig. 1. Link-time is divided in frames, composed of subframes. The minimum amount of resources that can be allocated to a device is a resource block (RB), corresponding to 12-subcarriers in a single subframe.

The research presented in this paper was supported by the Danish Council for Independent Research, grant no. 11-105159 "Dependable Wireless bits for Machine-to-Machine (M2M) Communications" and and grant no. DFF-4005- 00281 "Evolving wireless cellular systems for smart grid communications".

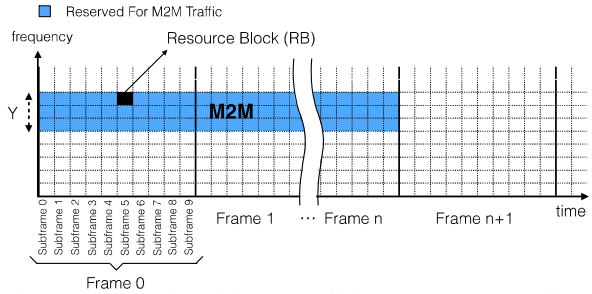

Fig. 1. Representation of the LTE uplink resource structure, where a set of RBs has been reserved for M2M purposes.

We assume that the resources are split into two pools, one reserved for M2M services (depicted in blue in Fig. 1) with one or multiple RBs in each subframe, and the other used for other services.

The M2M resource pool reoccurs with period TRI and is divided into pre-allocated and common pool, see Fig. 2a). We assume that there are N reporting devices. Each device is pre-allocated an amount of RBs from the pre-allocated pool, dimensioned to accommodate a single report and an indication if there are more reports, termed excess reports, to be transmitted within the same RI. The common pool is used to allocate resources for the excess reports and for all the retransmissions of the reports that were erroneously received. These resources are reactively allocated - we consider the LTE data transmission scheme, where each transmission has an associated feedback that can be used for this purpose[1]. The length of the M2M resource pool, pre-allocated pool and common pool, expressed in number of subframes, are denoted by X, X_P and X_C, respectively, see Fig. 2b), such that:

$$X = X_P + X_C = \alpha N + N_C.$$

where $\alpha \leq 1$ denotes the fraction of RBs per subframe required to accommodate a report and where X_C is chosen such that a report is served with a required reliability. The analysis how to determine X_C, given the required number of RBs per report, number of devices and reliability, is the pivotal contribution of the letter and presented in Section III.

[1] The minimum latency for the feedback is 6 subframes, which includes processing times at the base station and at the device, and which is negligible compared to the considered RIs that are of the order of 1000 subframes.

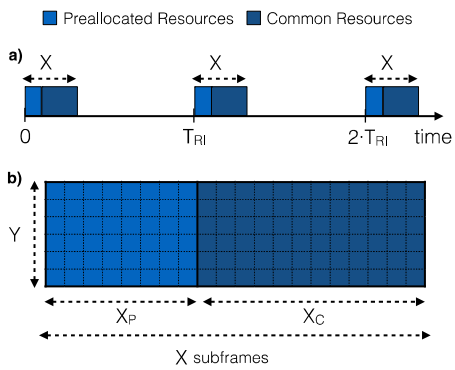

Fig. 2. a) Periodically occurring M2M resource pool. b) Division of M2M resource pool in the pre-allocated and common pool.

3. Analysis

Denote by $W_{i,j}$ a random variable that models the total number of transmissions of report j from device i; i.e., W includes the first transmission and any subsequent retransmissions due to reception failures. Further, assume that the maximum value of $W_{i,j}$ is L, applicable to all reports from all devices. The probability mass function (pmf) of $W_{i,j}$ can be modeled as a geometric distribution truncated at L:

$$P[W_{i,j} = k] = \begin{cases} p_e^{k-1}(1-p_e), & 1 \le k \le L-1, \\ p_e^{L-1}, & k = L, \end{cases}$$

where p_e is the probability of a reception failure.

The reporting of device i is modeled as a Poisson process U_i with arrival rate λ. As stated above, the first transmission of the first report of a device is sent in the pre-allocated pool, while all subsequent transmissions take place in the common pool. These include: a) potential retransmissions of the first report, and b) transmissions and potential retransmissions of all excess reports. Denote by R_i the random variable that corresponds to the total number of transmissions from device i requiring resources in the common pool:

$$R_i = \begin{cases} 0, & U_i = 0, \\ \sum_{j=1}^{U_i} W_{i,j} - 1, & U_i \ge 1, \end{cases} \quad (1)$$

The total number of transmissions of all N devices requiring resources from the common pool is:

$$R = \sum_{i=1}^{N} R_i.$$

The straightforward way to characterize R is to derive its pmf. However, as N is supposed to be very large, R is a sum of a large number of independent identically distributed random variables. Therefore, we apply the central limit theorem and assume that R is a Gaussian random variable, requiring characterization only in terms of the expectation and variance. We proceed by evaluation of $E[R]$ and $\sigma^2[R]$, and show in Section IV that this approach provides accurate results.

A. Expectation and Variance of R

The expectation of R is:

$$E[R] = E\left[\sum_{i=1}^{N} R_i\right] = N \cdot E[R_i] \quad (2)$$

Taking into account (1) and applying Wald's equation [3], it could be shown that:

$$\mathrm{E[R_i] = E[R_i|U_i = 0]P[U_i = 0] + E[R_i|U_i \ge 1]P[U_i \ge 1] = \frac{1-p_e^L}{1-p_e} - (1-e^{-1})} \quad (3)$$

Putting (3) into (2) yields $E[R]$. The variance of R can be derived in similarly, via identities related to the variance of the random sum of random variables [3]. We omit the derivation and present the final result:

$$\sigma^2[R] = N\left[\frac{(2L-1)p_e^{L+1} - (2L+1)p_e^L + p_e + 1}{(1-p_e)^2} + e^{-1}\cdot\left(1 - 2\frac{1-p_e^L}{1-p_e} - e^{-1}\right)\right].$$

B. Probability of Report Failure

Here we assess the probability of report failure, i.e., the probability that a report has not been successfully delivered after all attempted (re)transmissions. This probability depends both on the number of resources and the scheduling policy in the common pool. In order to avoid the particularities related to scheduling, we derive an upper bound on the probability of failure that is valid for any scheduling policy.

Denote by Φ the event of a report failure. Further, denote by l the number of required report transmissions, which includes the first transmission and all the required retransmissions. If we assume that the number of available resources in the common pool is infinite, then the report fails to be delivered only when the required number of transmissions exceeds L:

$$P_{\infty}[\Phi] = P_{\infty}[\Phi, l > L] = P[l > L] = p_e^L$$

However, in case when the common pool consists of X_C subframes, accommodating C transmissions, the probability of report failure is:

$$P[\Phi] = \sum_{k=1}^{L} P[\Phi, l = k] + P[\Phi, l > L], \quad = \sum_{k=1}^{L} P[\Phi|l = k]P[l = k] + p_e^L \quad (4)$$

Further, for 1 ≤ k ≤ L:

$$P[\Phi|l = k] = P[\Phi, R > C|l = k] + P[\Phi, R \le C|l = k] = P[R > C]P[\Phi|l = k, R > C],$$

where we used the fact that $P[\Phi, R \le C|l = k] = 0$, i.e., there is no report failure when the total number of required transmissions R is not greater then the capacity

of the common pool C. Regardless of the scheduling policy, it is always $P[\Phi|l = k, R > C] \leq 1$,

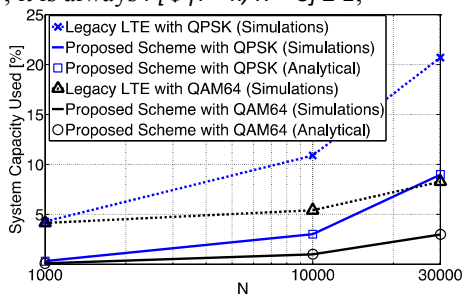

Fig. 3. Fraction of system capacity used for M2M services, when $P[\Phi] \leq 10^{-3}$, RI of 1 minute, RS of 100 bytes, bandwidth of 5 MHz.

leading to the following upper bound:

$$P[\Phi|l = k] \leq P[R > C]. \quad (5)$$

Finally, substituting (5) into (4) yields:

$$P[\Phi] \leq Q\left(\frac{C-\mu}{\sigma}\right)(1 - p_e^L) + p_e^L, \quad (6)$$

where $\mu = E[R]$, $\sigma = (\sigma^2[R])^{1/2}$, and Q(·) is Q-function.

4. Results

To validate the analytical bound derived in (6), we perform simulations with a random scheduler. We determine the fraction of LTE resources required for reliable services, defined as the ratio of RBs required for reliable M2M services and the total amount of RB. We assume a typical 5 MHz LTE system [4], typical individual LTE transmission error of $p_e = 0.1$ [5], and the maximum number of report transmissions L = 10. The probability of report failure is set to $P[\Phi] \leq 10^{-3}$, i.e., the desired reliability to at least 99.99%. Fig. 3 shows the performance of the proposed scheme, when report size RS is 100 bytes and the reporting interval RI is 1 minute, which is the most demanding case from [1]. It can be observed that for the lowest-order modulation (QPSK), up to 30K devices can be served with only 9% of system resources.

As comparison, Fig. 3 presents the performance of the legacy LTE, obtained using a LTE simulator with a typical 2 random access opportunities per frame [4]. The devices perform random access for every report, and the reports are sent in the RBs reserved for M2M. The legacy LTE requires about two times more resources than the proposed scheme; this is due to the uncertainty of the individual report arrivals and retransmissions, demanding a high amount of reserved RBs. In the proposed scheme, the individual reports are grouped (over a RI), and this aggregation exhibits far less uncertainty, requiring less reserved RBs for a reliable service.

Fig. 4 depicts the required fraction of system capacity for M2M service, when the RS varies between 100 bytes and 1 kbytes [1], the system bandwidth is set to

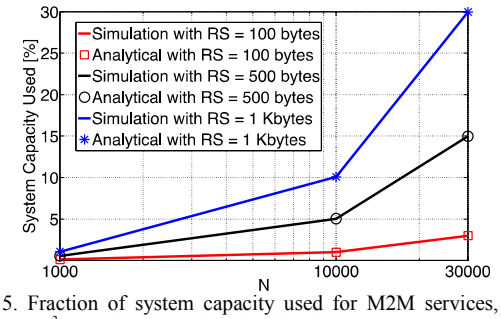

Fig. 5. Fraction of system capacity used for M2M services, when $P[\Phi] \leq 10^{-3}$, RI of 1 minute, bandwidth of 5 MHz, 64-QAM.

5 MHz, modulation scheme is 64-QAM, and $p_e = 0.1$. Obviously, the report size has a large impact in the results, demanding up to 30% of the system capacity in the worst case.

5. Conclusions

We have introduced a contention-free allocation method that relies on a pool of M2M-dedicated resources, reoccurring periodically in time. Within each occurrence, feedback is used to reactively allocate resources to each M2M device. The number of transmissions required by a device is random due to: (1) random number of reports arrived since the last reporting opportunity and (2) requests for retransmission due to channel errors. The objective is to dimension the resource pool of in order to guarantee certain reliability of the report delivery within the deadline. The fact that the resource pool is used by a massive number of devices allows to base its dimensioning on the central limit theorem. Promising results have been shown in the LTE context, where even with the lowest-order modulation only 9% of the system resources are required to serve 30K M2M devices with a reliability of 99.99% for a report size of 100 bytes.

References

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Channel-Hopping on Multiple Channels for Full Rendezvous Diversity in M2M Cognitive Networks

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1. Introduction

The Internet of Things (IoT) is enabled by machine-to-machine (M2M) communication networks that link sensors and other devices to each other, and to the Internet. M2M networks are often characterized by intermittent traffic, with small data packets, e.g. sensors reporting exceptional readings, and thus it may be more spectrally and power efficient to apply a cognitive radio (or dynamic spectrum access (DSA)) [1] protocol for M2M wireless access control.

In cognitive radio networks (CRNs), each SU is equipped with one or more radios to communicate with each other without causing unacceptable interference to licensed primary users (PUs). Since SUs are not assigned channels, they need to find a common frequency band (or channel) on which to establish a communication link. This process of SUs establishing a common available channel prior to data transmission is referred to as "rendezvous". Channel-hopping (CH) has been proposed as a practical method for rendezvous. Intelligently designed CH sequences can guarantee rendezvous between SUs with finite time-to-rendezvous (TTR) as long as there is at least one common available channel. Most work on CH based rendezvous [2-5] assume that, each SU is equipped with only one half duplex transceiver that is either listening to or transmitting on a channel at a time. However, multiple transceivers at each node may be preferable, since TTR is significantly reduced at the cost of extra radios. The only attempt to exploit multiple radios for CH based rendezvous is [6], in which SUs are assumed to have prior knowledge on the state of all channels. This is not a practical assumption in decentralized CRNs unless spectrum opportunities are static or slowly varying over time.

In this letter, we focus on the design of M-channel CH sequences to enable any pair of nodes to meet on all common available channels (i.e., full rendezvous diversity) in asynchronous environments. Unlike [6], we do not require SUs to have prior knowledge on channel states. For asymmetric systems, in which the nodes have pre-assigned roles as either transmitter or receiver, we propose an optimal CH sequence design attaining full rendezvous diversity in the shortest possible CH sequence period length. Then, by employing cyclically distinct bit sequences, we expand our design to symmetric CH systems that do not require the pre-assignment of sender and receiver roles.

2. System Model

We assume a DSA environment with an orthogonal channel set $\aleph=\{1,2,\ldots,N\}$ that is licensed to the primary network. Each SU is equipped with M half duplex transceivers and either listen to or transmit on M channels at a time. PU and SU activity is assumed to be slotted. A time-slot is defined as the duration that a secondary node can stay (i.e., either listen or transmit) on a set of M channels. An asynchronous system is one with misaligned period boundaries while the time-slot boundaries are aligned. CH schemes are commonly evaluated by their rendezvous diversity, which indicates the minimum number of guaranteed rendezvous channels over all pairs of CH sequences. Some channels may not be available due to the presence of PU signals, or SUs may have different sets of available channels due to the spatial variation in PU signal levels, and co-channel interference from other SUs. To mitigate the effects of interference and spatial variation of channel availability, ideally, a CH system should have full rendezvous diversity in the shortest possible CH sequence period. For a detailed discussion of rendezvous diversity, readers are referred to [2].

3. Asymmetric CH Sequences

In asymmetric systems, secondary nodes have pre-assigned roles as sender or receiver and generate their CH sequences according to their role. The design objective is to enable any sender node to rendezvous with any receiver node on all common available channels with minimal TTR. The basic idea behind the sequence design is to keep the receiver node listening to the same set of channels for a number of consecutive time slots that is long enough for a sender node to visit all channels in $\aleph$. Meanwhile, each sender node continuously jumps to disjoint channel sets of size M until each channel in $\aleph$ is visited once. This procedure is repeated N/M times until the receiver node completes waiting on all channels in $\aleph$.

Receiver Sequence Construction

1. $\aleph$ is partitioned into subsets $v_0, v_1, \ldots, v_{P-1}$ each containing M consecutive integers.
2. Then, P different subsequences $V_0, V_1, \ldots, V_{P-1}$

are generated by repeating the same elements of each subset P times. (e.g. $V_0 = v_0||v_0||v_0 = \{\{1,2\},\{1,2\},\{1,2\}\}$, where || is defined as the concatenation operator to concatenate elements or sequences.)

3. P subsequences are concatenated in a random order. The final receiver sequence consists of $T=P^2$ elements. (e.g. as shown in Fig. 1, $\boldsymbol{V}^i = V_2||V_0||V_1 = v_2||v_2||v_2||v_0||v_0||v_0||v_1||v_1||v_1 = \{\{5,6\},\{5,6\},\{5,6\},\{1,2\},\{1,2\},\{1,2\},\{3,4\},\{3,4\},\{3,4\}\}$)

Sender Sequence Construction

1. $\aleph$ is partitioned into subsets $u_0,u_1,\ldots,u_{P-1}$ such that each subset contains integers that have the same remainder when divided by P.
2. To generate the subsequence, each sender node concatenates the elements of these P subsets in a random order. (e.g. $U^i = u_1||u_0||u_2 = \{\{1,4\}, \{3,6\},\{2,5\}\}$)
3. The subsequence U^i is repeated P times to obtain the final sender sequence. (e.g. $\boldsymbol{U}^i = U^i||U^i||Ui = u_1||u_0||u_2||u_1||u_0||u_2||u_1||u_0||u_2 = \{\{1,4\},\{3,6\},\{2,5\},\{1,4\},\{3,6\},\{2,5\},\{1,4\},\{3,6\},\{2,5\}\}$)

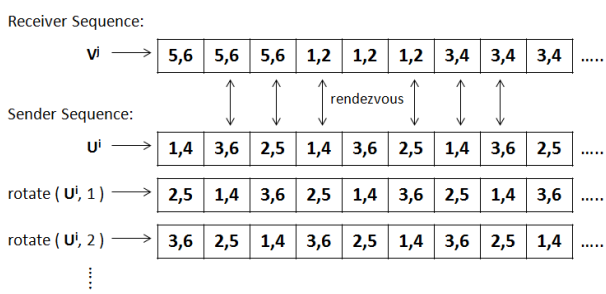

Figure 1. An example of receiver and sender sequences for $N=\{1,2,3,4,5,6\}$, $M=2$ and $P=3$.

It can be shown that the CH sequences generated by the above methods have a period of $P^2=N^2/M^2$ and rendezvous diversity N. Hence, when M radios are used at each SU, the CH sequence period can be reduced by a factor of M^2. Roughly speaking, this will reduce TTR by M^2 suggesting a significant improvement over CH on a single channel.

4. Symmetric CH Sequences

For full rendezvous diversity in such symmetric systems, rather than generating only two overlapping CH sequences, a unique CH sequence should be generated for each node, such that it is enabled to rendezvous with all other nodes on all common available channels. We can simplify the symmetric M-channel CH sequence design problem by recalling that overlapping $\boldsymbol{U}$ and $\boldsymbol{V}$ sequences provide full rendezvous diversity as claimed in the previous section. This observation brings the idea of generating symmetric CH sequences based on the concatenations of a certain number of $\boldsymbol{U}$ and $\boldsymbol{V}$ sequences. Thus, CH sequences of symmetric systems can be constructed based on cyclically distinct (CD) bit sequences where the bits represent $\boldsymbol{U}$ and $\boldsymbol{V}$ sequences. Given that all nodes are assigned CD bit sequences, the following algorithm describes the construction of CH sequences for symmetric systems.

Symmetric CH Sequence Construction

1. Each *"0"* in the bit sequence B^i is replaced with the concatenation of two $\boldsymbol{U}^i$ sequences while each *"1"* in B^i is replaced with the concatenation of two $\boldsymbol{V}^i$ sequences.
2. The resulting sequence consisting of blocks of $\boldsymbol{U}^i||\boldsymbol{U}^i$ and $\boldsymbol{V}^i||\boldsymbol{V}^i$ sequences is used as the CH sequence for node i.

The symmetric CH sequences generated by the above method can be shown to have a period $T \leq 2nP^2$ and rendezvous diversity N, where the total number of nodes is less than or equal to $2^n/n$.

5. Simulation

In this section, we compare the performance of the proposed asymmetric and symmetric CH schemes with *role-based parallel sequence (RPS)* proposed in [6]. The plots of RPS are based on the analytical upper bounds on TTR as provided in that paper. The impact of the number of half duplex transceivers (i.e., M) at each SU on TTR is observed in Fig. 2, where the total number of available channels is set to $N=24$. TTR decays more rapidly in our proposed CH schemes than it does in RPS as M increases. Note that, RPS assumes that the SUs have prior knowledge of the states of all channels while our schemes are free from such an assumption.

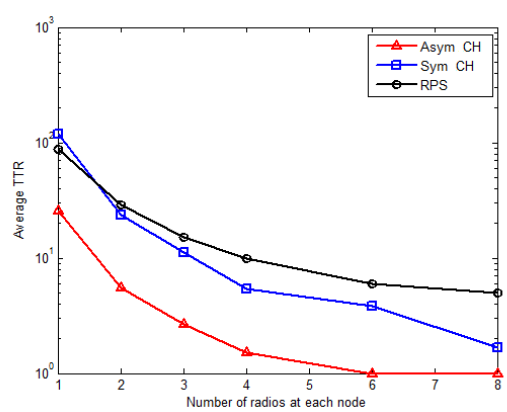

Figure 2. Average TTR versus number of half duplex transceivers at each node when *N=24*.

In Fig. 3, we compare the performance of the proposed CH schemes with RPS as the number of available channels between SU pairs varies. Each SU is assumed to visit *M=3* among *N=12* channels at a time. Thanks to full rendezvous diversity, the proposed CH schemes are robust to channel unavailability and TTR increases slowly with the number of unavailable channels. Both asymmetric and symmetric CH outperform RPS in terms of average TTR.

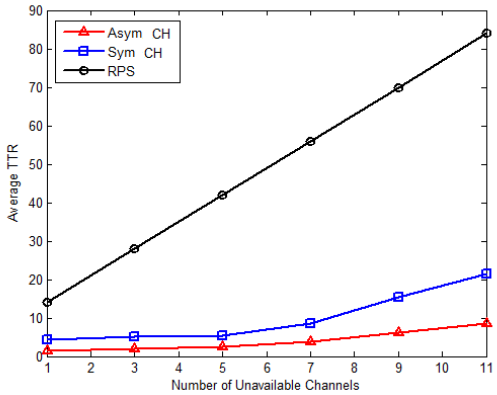

Figure 3. Average TTR versus number of unavailable channels between SU pairs when *N=12, M=3*.

6. Conclusion

In this letter, the number of transceivers equipped by each SU was shown to have a significant impact on average TTR. The proposed CH schemes can adapt to asynchronous environments and enable rendezvous between any pair of nodes with different roles. Both of the proposed CH schemes outperform RPS in terms of average TTR.

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Machine-to-Machine (M2M) Communications for Smart Grid

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1. Introduction

Machine-to-Machine (M2M) communications are characterized by fully automatic data generation, exchange, processing and actuation among intelligent machines, without or with low intervention of humans [1]. Low human intervention requires self-x capabilities, including self-organization, self-configuration, self-management, and self-healing. A large number of machines with diverse functionalities are autonomously organized to constitute an M2M network. An M2M network interconnected to the Internet and deployed in the physical world for sensing and controlling purposes describes a picture of the Internet of Things (IoT). In the near future, M2M networks are envisioned to be widely utilized in many fields of pervasive applications, including industrial and agricultural automation, healthcare, transport systems, electricity grids, etc [6][10].

In many M2M communications applications, machines are expected to be low cost, so that they can be easily embedded in real fields and extensively deployed in a large scale. The machine hardware constraints and the application-driven demands pose a number of unique challenges in realizing seamlessly connected, efficient, and reliable M2M communication. Some of the key challenges include machines heterogeneity, resource constraints, and Quality-of-Service (QoS) support.

In this article, we will present our visions on a new M2M communications paradigm, i.e., Cognitive radio enabled M2M (CM2M), and then point out its potentials in the smart grid. We first identify the motivations in exploiting cognitive radio technology in M2M communications from different aspects, including technical, applications, industry support, and standardization perspectives. After that, a CM2M communications architecture for the smart grid is presented.

2. Why Cognitive Radio in M2M?

There are several motivations in using cognitive radio [2] in M2M communications. These motivations are categorized into technical challenges and opportunities, applications, industrial support, feasibility, and standardization activities in international organizations.

Technical Perspective We present four key technical challenges in M2M as well as motivations in promoting CM2M: massive number of machines, green requirement, interference, and machine heterogeneity.

Massive Number of Machines — One of the most revolutionary applications of cognitive radio is to address spectrum scarcity issue in wireless communications. Eliminating spectrum congestion is one of the primary reasons for applying cognitive radio in M2M communications. The main challenge in M2M communications is the ever increasing number of machines. This poses a significant challenge for any existing communication network. Cognitive radio supports large-scale data transmission by utilizing larger parts of the spectrum.

Green Requirement — A machine is a low-cost and low-power device, which is designed to work for several years without battery replacement. In this case, energy saving is extremely important by optimizing M2M nodes' sensing and processing, and ultimately prolong the lifetime of the whole M2M communications network. Cognitive radio has been demonstrated to be green [3]. Cognitive machines in a secondary network are capable of adaptively adjusting their transmission power levels based on the operating environments, without interfering with the primary network and at the same time not causing spectrum pollution. Such intrinsic context-aware and adaptable functionality make cognitive radio a key enabler for the future generation environment-friendly radio systems.

Interference — There is increasingly intensive interference in M2M communications, including the internal wireless signal inference among unlicensed systems operating in the ISM frequency band, and the external electromagnetic interference from electronic equipments in industrial settings. The performance of M2M communications may be seriously degraded due to such self-existing and co-existing interference. By leveraging the software-reconfigurability of cognitive radios, machines are able to rapidly switch among different wireless modes, and hence potentially be allowed to dramatically reduce or even avoid the interference with other machines or the external radio environment.

Machine Heterogeneity — An M2M network generally comprises a large number of different machines as well as diverse services, which may cause significant diversity in network protocols and data formats. The cognition ability is beneficial for M2M communications to deal with the machine and protocol

heterogeneity. An M2M network will be more efficient and flexible if all machines are smart enough to communicate with the others freely.

Applications Perspective

Smart Power Grid — Networked smart meters and advanced metering infrastructure are enabled by M2M communications in the smart grid [7, 8]. It is estimated that the amount of generated energy-related data will be up to tens of thousands of terabytes in the near future [9]. This poses a significant challenge for any existing communication network as well as the future smart grid network. The usage of cognitive radio in the smart grid potentially improves spectrum utilization and communication capacities to support large scale data transmissions. In addition, for smart meters that has relatively low data volumes, CM2M has the advantages of saving energy consumption to enable greener power grids [3]. Wind farm area networks are normally deployed in remote areas, where there are plenty of TV white spaces. CM2M over TV white spaces becomes an ideal choice in this scenario. Last but not least, there are also other promising applications where CM2M may significantly improve system performance and adaptability, including eHealthcare, Intelligent Transport Systems, home multimedia distributions and sharing, urban broadband services, rural broadband services, land security, video surveillance, and civil infrastructure.

Industry Perspective

In the telecommunication industry, there are very active efforts in developing cognitive radio enabled M2M communications, in particular M2M over TV white spaces (TVWS). Here, TV white spaces refer to unused spectrum bands in the TV bands [5]. Spectrum Bridge (http://spectrumbridge.com/) has developed, and is currently trialing, a TV white spaces geolocation database, and is also developing products over TV white spaces, which enables both private an enterprise users to seamlessly roam between different networks without having to reconfigure devices. Neul (http://www.neul.com) has developed M2M communications networked solutions over TV white spaces. In a number of trials around the world, Neul is demonstrating smart city concepts such as managing the urban infrastructure, smart metering applications, and transport telematics. British Telecom (http://www.bt.com) is researching the exploitation of TV white spaces as an option to provide broadband access to rural communities in the UK.

3. M2M for Smart Grid

Figure 1 shows the proposed CM2M architecture for the smart grid. We focus on three sub-areas where CM2M plays an important role: Field Area Networks (FANs), Home Area Networks (HANs), and Neighborhood Area Networks (NANs).

CM2M for Renewable Energy Field Area Networks

A unique characteristic of the smart grid is the integration of distributed renewable energy sources (e.g., solar and wind power) into the power grid. Renewable energy sources, e.g., wind energy, are normally deployed in remote and isolated areas. Wind turbines are also deployed offshore. It is envisioned that there are three types of M2M communications in wind farm FANs: M2M among the turbins in the wind farm, the smart grid concatenator), and M2M between the wind farm and the local community to provide suitable green energy. Due to remote geo-locations, there are usually plenty of TVWS. CM2M over TVWS becomes an ideal choice for the communications in the renewable energy FANs. Furthermore, CM2M over TVWS is very suitable for the communications between machines and the control center (or the smart grid concatenator) since IEEE 802.22 is designed for TVWS and for rural long-distance communications.

CM2M for Grid Protector Field Area Networks

In the smart grid, there are a number of power grid protectors. The grid protectors need to quickly execute protection algorithms upon the detection of fluctuation, disturbances, or power outage. In particular, they are very crucial to signal to areas that have to be isolated. It is envisioned that the interconnection of grid protectors is able to substantially improve the capabilities of monitoring, detection, and protection. The integration of CM2M will add flexibility into grid protectors FANs in both deployment and operation procedures. The distribution systems can be timely protected and post-fault controlled with large scale renewable energy generation units and power electronic converters. With quick signaling, a local system can stably operate in an island mode if the high-voltage power system fails and restore normal operations as quickly as possible. This will minimize the possibility of total loss of power in an abnormal situation.

CM2M for Home Area Networks

Home area networks communicate with various smart devices to provide energy efficiency management and demand response. The HAN consists of a cognitive home gateway (HGW), smart meters, sensors, actuators, and other intelligent devices. HANs are fundamental components to enable two-way communications to provide demand response management (DRM) services in the smart grid. DRM is a crucial component in the green smart grid. DRM refers to mechanisms that encourage consumers to streamline their demand, thereby reducing the peak demand for electricity [4]. Normally, power generation systems are sized to correspond to peak demands (plus margin for

forecasting errors and unforeseen events). By reducing the peak electric load, DRM helps to reduce the need for more power plants, lowering CO2 and other pollutants and hence achieve the green smart grid. In the future smart power grid, the DRM formulation should be extended to additionally consider the integration of renewable energy sources, multiple energy sources, and communications.

CM2M for Neighborhood Area Networks

A smart grid neighborhood area network is composed of several HANs. In a smart grid NAN, there is a concatenator that communicates and manages several HANs within its coverage. The smart grid concatenator communicates with the HAN gateways over unlicensed bands, e.g., TVWS. The introduction of a concatenator in this infrastructure facilitates the spectrum discovery and utilization. The concatenator may also communicate with renewable energy FANs to facilitate demand response management in the community. In the case of an outage of the fixed smart grid concatenator, a mobile concatenator (e.g., in a truck) may be deployed and utilized as an alternative solution.

4. Conclusion and Future Work

In this article, we promoted the new paradigm of cognitive machine-to-machine (CM2M) communication, by exploiting cognitive radio technology in M2M communications. We first motivated the promotion of CM2M from different perspectives, including technical, applications, industry support, and standardization. Then, we introduced the CM2M network architecture. We showed that different CM2M systems may want to co-exist, e.g., exploiting TV white spaces, and we discussed potential solutions to this challenge. We presented the potentials of CM2M for the smart grid in renewable energy field area networks, grid protector field area networks, home area networks, and neighborhood area networks.

The proposed architecture and solutions have yielded significant results and momentum for further developments. Application-driven solutions need further consideration in the mission critical smart power grid. Reliability and timeliness are two key metrics that may be integrated in the QoS study. CM2M system co-existence in TVWS is a new research challenge, which needs careful design to ensure fair and efficient sharing among heterogeneous users. The security issue is an interesting research topic in various CM2M applications which may have different and their own unique vulnerabilities.

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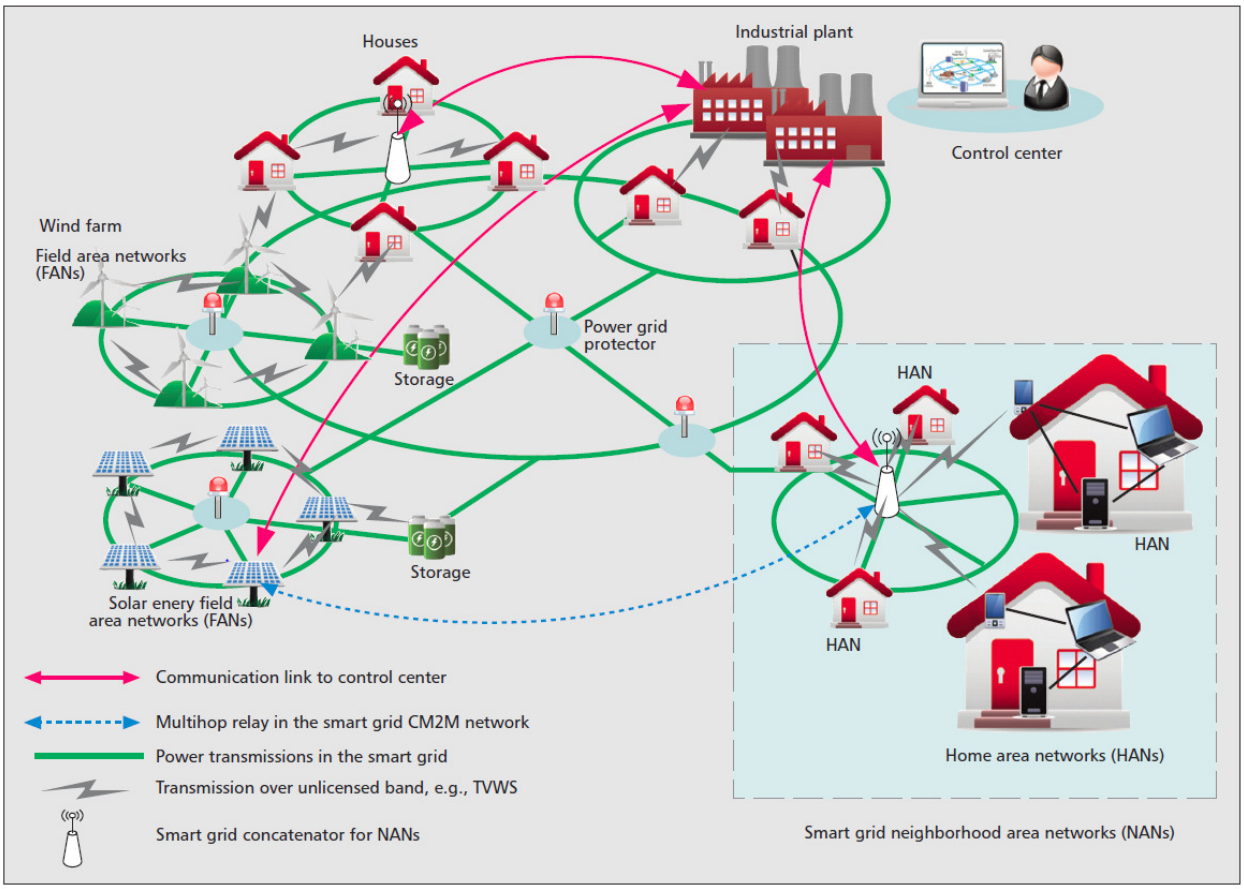

Fig.1 M2M for Smart Grid

Coalition Formation for Heterogeneous Machine Type Communications

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1. Introduction

Machine-to-machine (M2M) or machine-typecommunications (MTC) has emerged as a new communication paradigm to support various automated system operations without or with minimal human interaction, e.g., in Internet of Things (IoT) and smart power grids. M2M communications will be different from human-to-human (H2H) communications in terms of traffic pattern. Firstly, data transmission in M2M communications will be small in size, but high in frequency (e.g., in environmental monitoring and smart meter reading applications). Most of M2M traffic is in the uplink direction. Secondly, M2M devices will be mostly inactive and become active only when there is a need for data transmission. M2M devices and H2H users can coexist in the same network such as the emerging long-term evolution (LTE). The LTE network supports MTC through the use of efficient random access (RA) methods for a large number of MTC [1], [2] user equipments (UEs). Although the random access mechanisms (e.g., contention-based and contention-free random access) are defined in the standards, there are many design considerations related to the radio resource management that need to be studied.

In this letter, we present the coalitional game model for eNodeB selection and coalition formation for relay transmission. We consider the small cell network environment, where a macrocell is underlaid by small cells (e.g., femtocells). MTC traffic can be offloaded to the small cells to improve the performance of the overall networks. In addition, MTC UEs can form coalitions and perform relay transmission to reduce congestion in the network. The algorithm based on the switch rule in coalitional game for the MTC UEs to select the eNodeB and form a coalition for relay transmission is presented. The Nash-stable coalitions are considered as the solution.

2. System Model

We consider a macrocell in heterogeneous networks (HetNets) with a macro eNodeB (Fig. 1). The macrocell is underlaid by multiple small cells (e.g., femtocells) operated by small-cell eNodeBs. There are two types of a UE, i.e., machine-type-communications (MTC) and human-to-human (H2H). The H2H and MTC UEs require preambles to initiate a connection to the macro or small-cell eNodeB for data transmission. The H2H and MTC UEs can contend to obtain resource blocks through the random access. We assume that the small cells are operated on an open access mode in which the small-cell eNodeB always accepts connection requests from the H2H and MTC UEs. The H2H UEs are assumed to connect to the small-cell eNodeB when the H2H UEs are in the coverage area of that small-cell eNodeB. Otherwise, the H2H UEs will connect to the macro eNodeB. Alternatively, the MTC UEs can choose to connect to the small-cell eNodeB or macro eNodeB even if the MTC UEs are in the coverage area of the small-cell eNodeB. This selection depends on the received performance.

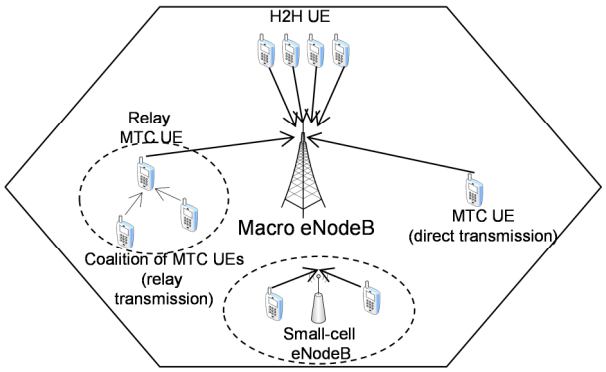

Fig. 1: System model.

The MTC UEs with an alternative transmission interface (e.g., a short-range transceiver) can negotiate and form coalitions to cooperatively relay packets of each other to the target eNodeB. If the MTC UEs agree to form a coalition, one MTC UE called "MTC UE relay" will be selected. Other MTC UEs will locally transmit their packets to the MTC UE relay using a short-range transceiver. The MTC UE relay receives the packets and stores them in its buffer together with the data packets generated by the MTC UE relay itself. Then, like the MTC UEs with direct transmission to the eNodeB, the MTC UE relay performs the random access to obtain a preamble so that the connection to the target eNodeB can be initiated and the packets stored in the buffer of the MTC UE relay can be transmitted. Using the local and relay transmission can reduce the energy consumption of the MTC UEs and congestion of the network.

3. Coalition Formation

In the system model under consideration, MTC UEs have to make a couple of decisions. Firstly, if the MTC UEs are in the coverage area of a small-cell eNodeB,

then the MTC UEs have to decide whether to connect to the macro eNodeB or small-cell eNodeB. Secondly, if the MTC UEs have the short-range transceiver and are in the transmission range of each other, the MTC UEs can decide to perform relay transmission to a target eNodeB.

Coalition Formation

Based on the perceived performance of the random access, the MTC UEs in a macrocell can decide to select macro or small-cell eNodeB and form coalitions to perform relay transmission. In the following, we introduce the eNodeB selection and coalition formation for relay transmission of MTC UEs based on the non-transferable utility (NTU) coalitional game. The coalitional game is defined by a pair (I,V), where I is a finite set of players and V is a set of value function of all possible coalitions $C \subseteq I$. In this case, V (C) is composed of the payoff vectors that the players in the coalition C can achieve. The proposed coalitional game is in a partition form. The players of the game are MTC UEs in the macrocell. The payoff is utility of an MTC UE. The coalitional game is an NTU game since the payoff (e.g., throughput) cannot be arbitrarily apportioned among players. The MTC UEs (i.e., players) are rational to form coalitions such that their individual payoff is maximized.

We have the following given coalitions.

M_d is the singleton coalition with the member MTC UE performing direct transmission to the macro eNodeB, where d and D are the index and the maximum number of corresponding coalitions, respectively.

• N_j is the coalition whose member MTC UEs perform relay transmission to the macro eNodeB, where j and J are the index and the maximum number of corresponding coalitions, respectively.

• $S_{s,b}$ is singleton coalition with the member MTC UE performing direct transmission to the small-cell eNodeB s, where b and B are the index and the maximum number of corresponding coalitions, respectively.

• $L_{s,l}$ is the coalition whose member MTC UEs perform relay transmission to the small-cell eNodeB s, where l and Ls are the index and the maximum number of corresponding coalitions, respectively.

S is the total number of small cells underlaying the macrocell. Fig. 1 also shows the notations of coalitions in the network model under consideration.

Different actions will be taken by the MTC UEs in different coalitions. They can be referred to as the "action-specific coalition". Specifically, the MTC UE in the coalition M_d observes the system information (e.g., available preambles) from the macro eNodeB and performs random access to connect to the macro eNodeB. Similarly, the MTC UE in the coalition $S_{s,b}$ observes the system information from the smallcell eNodeB s and tries to connect to that small-cell eNodeB. By contrast, the MTC UEs in the coalition N_j choose an MTC UE relay to receive packets from other MTC UEs in the same coalition. The MTC UE relay performs random access to connect to the macro eNodeB. Similarly, the MTC UEs in the coalition $L_{s,l}$ choose an MTC UE relay to perform random access to connect to the small-cell eNodeB s.

We consider a preference relation or preference order [3] for MTC UEs to make their decisions. Specifically, for any MTC UE $i \in I$, a preference relation is denoted by $\succcurlyeq_i$. Specifically, $C \succcurlyeq_i D$ represents that the MTC UE i prefers being a member of coalition C over coalition D or prefers being a member of coalitions C and D equally. $C \succ_i D$ indicates that the MTC UE i strictly prefers being a member of C over D. The preference relation is defined based on the individual payoff of an MTC UE, i.e.,

$$C \succcurlyeq_i D \Leftrightarrow U_i(C) \geq U_i(D) \qquad (2)$$

where $U_i(C)$ is the utility of MTC UE i when it is a member of coalition C. The utility function considered in this paper will be defined later in (3).

The coalition formation of MTC UEs is based on the switch rule [4] which is defined as follows: The MTC UE i will leave its current coalition D and join another coalition C if and only if $C \cup \{i\} \succ_i D$ and $C \cup \{i\} \succcurlyeq_{i'} C$ for all $i' \in C$. Then, the new coalitions become $(D', C') = (D \setminus \{i\}, C \cup \{i\})$. Specifically, the MTC UE i will switch from the coalition D to C if the MTC UE i strictly gains higher payoff and the other MTC UEs i' in the target coalition C are not worse off. Note that the non-singleton coalition corresponds to the relay transmission. In practice, if the current members of the coalition C do not want the new MTC UE i to join their coalition (i.e., the current member MTC UEs i' will gain lower payoff), the MTC UE relay of that coalition can refuse to accept the packet from the MTC UE i.

Utility

We consider the utility which is a function of the performance measures to make the decision on the eNodeB selection and coalition formation for relay transmission. Although the utility function can be defined based on the different performance measures, in this paper, we consider the throughput-, cost-, and energy-sensitive MTC UEs. Therefore, the utility function of an MTC UE i is defined as follows:

$$U_i(C) = w_1\tau(C) + w_2\left(1 - \frac{T(C)}{|C|} - E_{sm}(C)\right) - \frac{F}{|C|} \quad (3)$$

where τ(C) is the normalized throughput and T(C) is the duty cycle (i.e., the proportion of time that MTC UE is

in the active mode), where i ∈ C. |C| is the number of members in the coalition C. The normalized throughput and duty cycle are defined as the functions of the current coalition C of the MTC UE. F can account for the additional cost (e.g., a connection fee that the corresponding eNodeB charges to the MTC UE and an overhead due to coalition formation). When there is more than one MTC UE in a coalition N_j or Ls;l (i.e., to perform relay transmission), the MTC UEs will take turns to become the MTC UE relay to receive packets from other MTC UEs in the same coalition and forward to a target eNodeB. As a result, the duty cycle is divided by the total number of MTC UEs in the same coalition. $E_{sm}(C) = E$ is the energy consumption if the short-range transmission is used, where E is a constant of energy consumption for a short-range transmission. w_1 and w_2 are the weights of the normalized throughput and energy efficiency factor, respectively. Note that the utility function defined in (3) is used when MTC UE I can be a member of a coalition C. However, if the MTC UE I cannot be a member of any coalition C', then $Ui(C') = -\infty$ for the following cases

· If the MTC UE i is not in a coverage area of a small-cell eNodeB s, then $U_i(S_s) = U_i(L_{s,l}) = -\infty$.

· If the MTC UE i is not equipped with an alternative short-range transceiver, then $U_i(N_j) = U_i(L_{s,l}) = -\infty$.

4. Performance Evaluation

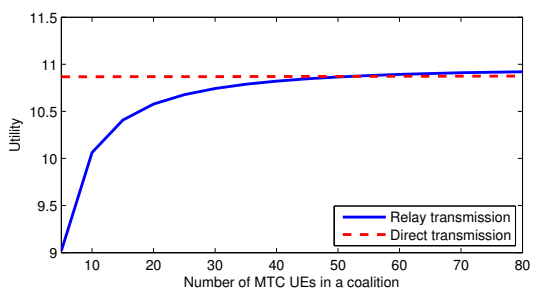

Fig. 2: Utility of the MTC UE with direct and relay transmission.

When MTC UEs have alternative short-range transceivers, the MTC UEs can form coalitions such that their packets can be aggregated and forwarded (i.e., relayed) to a target eNodeB. We consider two cases for the MTC UE, i.e., when it acts as a single node transmitting directly to the eNodeB and when it forms a coalition with other MTC UEs and performs relay transmission to the eNodeB. Fig. 2 shows the utility of the MTC UE for such cases. In Fig. 2, we consider the total number of MTC UEs in a macrocell to be 200. There is one coalition whose size is varied, while the rest of MTC UEs perform the direct transmission to the eNodeB. Note that there is no small cell in this case so that the effect of forming a coalition can be clearly focused.

When the coalition becomes bigger (i.e., more MTC UEs join the coalition), the utility of the MTC UE in the coalition increases (Fig. 2). This result is from the fact that when the coalition size is small, the contention with other MTC UEs with direct transmission is severe, and hence the throughput is low. Also, the MTC UEs in the coalition have an overhead due to the short-range transmission, reducing their utility. However, when more MTC UEs join the coalition, the contention becomes lighter, resulting in higher throughput. We observe that there exists the range of a coalition size such that the utility of the MTC UEs in the coalition will be higher than that with direct transmission. The coalitions can be formed using the proposed algorithm.

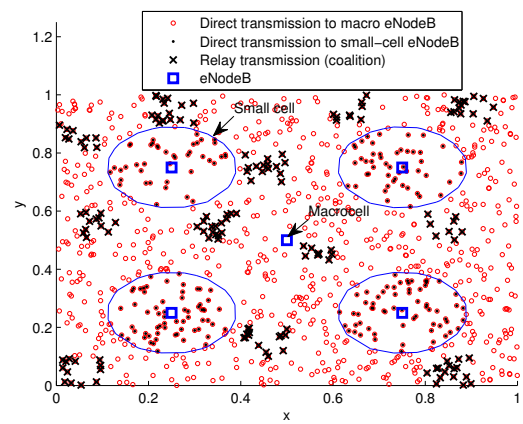

Fig. 3: A snapshot of the network.

The snapshot of the network with 12 coalitions and 4 small cells is shown in Fig. 3. In this snapshot, we observe that none of MTC UEs connected to a small-cell eNodeB forms a coalition. Since there are a few MTC UEs in each small cell, the congestion does not happen, and hence there is no need for MTC UEs to form a coalition which could incur an overhead.

5. Conclusion

We have considered the issue of Evolved Node B (eNodeB) selection and coalition formation for relay transmission by MTC user equipments (UEs). The non-transferable utility (NTU) coalitional game model has been formulated and the algorithms for MTC UEs to select eNodeB and perform relay transmission have been proposed. The performance evaluation has revealed a few interesting results. For example, when the MTC UEs spend more time in an inactive mode (i.e., to reduce energy consumption), the performance in terms of throughput improves. This is due to the fact that the congestion can be alleviated due to fewer active MTC UEs in the network. However, the delay performance of such MTC UEs can become worse.

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INDUSTRIAL COLUMN: SPECIAL ISSUE ON SMART GRID

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The smart grid is an emerging research field. The smart grid is widely considered to be the next-generation electricity grid. The smart grid will be integrated with a variety of state-of-the-art enabling information technologies covering the areas of embedded sensing, broadband wireless communication, pervasive computing, and adaptive control, to significantly improve the efficiency, sustainability, security, and stability of the electrical grid.

An efficient and reliable communication architecture plays a crucial role in the smart grid to establish two-way information transmission between customers and utilities. Smart meters are basic components in the smart grid, which are capable of collecting and delivering power consumption information to remote utilities much more efficiently than conventional meters. Smart meters will measure the load profile and demand, store historical information, and act as meter-as gateway or meter-as-device. Smart meters/sensors/actuators will be strategically implemented in the smart grid network. With the help of smart meters, utilities are able to monitor the peak load through consumer participation, and control various appliances and industry electricity consumption for optimal power generation and consumption. Live power consumption information will be exploited to vary prices in order to shift the peaks of usage as well as reduce cost. Three fundamental functionalities are desirable for the communications infrastructure of the smart grid: sensing, transmission, and control. The smart grid is usually deployed in a considerably large geographical field. Accordingly, the communications infrastructure of the smart grid has to cover the entire region with the intention to connect a large set of nodes.

This special issue of E-Letter focuses on the recent progresses of smart grid communication, control, computation and optimization. It is the great honor of the editorial team to have four leading research groups, from both academia and industry laboratories, to report their solutions for meeting these challenges and share their latest results. Since smart grid development is closely related to geolocation, we have invited authors from different geolocation to make contributions, including researchers from North America, Europe, and China.

In the first article titled, "Wireless Visual Networks Application in Smart Grid", Hassnaa Moustafa and V. Srinivasa Somayazulu from Intel Corporation presented their views on using wireless visual networks in the smart grid. Exploiting the advancements in multimodal wireless sensor technologies and the huge increase in smart applications enables creation of smart environments that interact with Smart Grid operations to provide users a superior experience. Sensors provide key contextual inputs to learn more about users and environment aiming to improve robustness, reliability and better energy savings. The extraction, analysis and communication of these visual context cues will be increasingly enabled in low power SoCs, and can provide important information to complement and supplement information from other sensors.

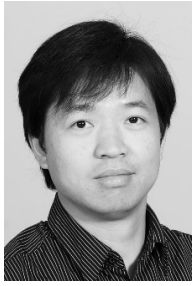
The second article "Distributed Direct Load Control for Large-scale Residential Demand Response" is contributed by Chen Chen, Jianhui Wang and Shalinee Kishore. This is a collaborating study between Argonne National Laboratory and Leigh University, USA. This article proposes an innovative two-layer communication-based distributed direct load control approach for large-scale residential demand response. The authors employ average consensus algorithms in the upper layer network to allocate target power consumption levels for each building. The EMC (energy management controller) in each building then schedules appliance operations according to the local power consumption target. The protocol integrates these two layers seamlessly and also enables non-intrusive operation of appliances.

The third article is "Last-mile Communication Solutions for China Southern Power Grid" from Qilin Guo, Rong Yu and Yan Zhang. This work is accomplished by the tight collaboration between Guangdong Electric Power Design Institute of China Energy Engineering Group; Guangdong University of Technology, China; and Simula Research Laboratory, Norway. This paper presents the unique challenges of smart grid development in China. Dedicated wireless broadband network is regarded as a potential solution for massive data collections and real-time downlink controls in power distribution networks in China. The authors also discuss trial projects in China southern

power grid, and the practical challenges.

The fourth article is "Asymptotic Optimal Online Energy Distribution in the Smart Grid" is contributed by Yu Wang, Shiwen Mao, and R.M. Nelms from Auburn University, USA. This article focuses on optimal real-time energy distribution in smart grid. With a formulation that captures the key design factors of the system, the authors first present an offline algorithm that can solve the problem with optimal solutions. Then, the authors develop an online algorithm that requires no future information about users and the grid. Results show that the online solution converges to the offline optimal solution asymptotically and almost surely. The proposed online algorithm is evaluated with trace-driven simulations.

While this special issue is far from delivering a complete coverage on this exciting research area, we hope that the four invited letters give the audiences a taste of the main activities in this area, and provide them an opportunity to explore and collaborate in the related fields. Finally, we would like to thank all the authors for their great contribution and the E-Letter Board for making this special issue possible. Special thanks go to Prof. Shiwen Mao for his great support and patience.



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Wireless Visual Sensor Networks Applications in Smart Grid

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1. Introduction

We are witnessing the initial stages of the revolution in energy management through green energy that is changing not only the way our society is producing energy but also consuming energy. There is emerging widespread rise in Smart Grid technologies, e.g. [1]. A key component of Smart Grid technologies is the demand side management by enabling devices in the utility network with sensors to gather data plus two-way communications between these devices and the utility's operations center. Most commonly, these sensors are power meters, voltage sensors, light level detectors, movement/occupancy sensors, etc. In this paper we focus on smart and context-aware energy demand management in Smart Grid through enabling advanced sensing techniques, interfaces to smart devices in the home as well as the Internet and to the Cloud. In particular we consider applications of wireless visual sensor networks, e.g. [2] in Energy Management Systems (EMS) for Smart Grid. The applications span a wide range e.g. Home energy Management System (HEMS), smart buildings/offices and smart roads.

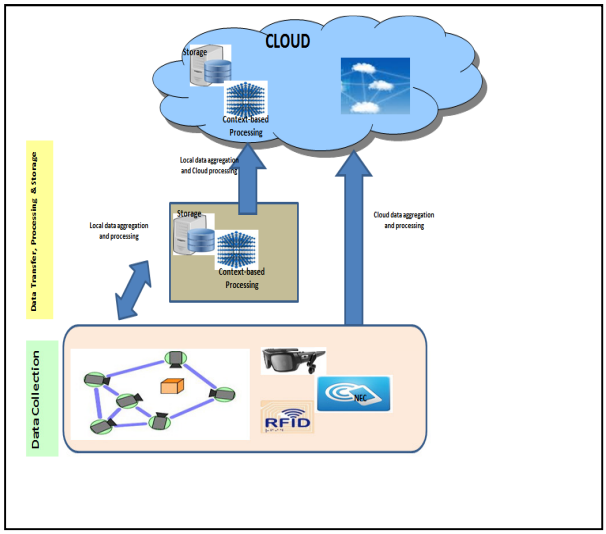

Fig.1 WVSN in Smart Grid

The view we present is of Wireless Visual Sensor Networks (WVSN) combined with other sensors in multimodal sensor packages or systems, which extract contextual information about users and their environment, interactions, activities, etc. and interact with Smart Grid operations. This result in benefits to both users, system operators, and society as a whole – as users' experience is improved while energy conservation, load management etc. are better served. In the following sections we present an overview on WVSN in Smart Grid illustrating potential applications and use-cases, and describing the deployment architecture and end-to-end communication between the sensors and between the sensors and the cloud (including processing, storage and intelligent decision triggering). We also provided key requirements and technical challenges on sensors and data processing.

2. Overview on WVSN in Smart Grid

Figure 1 illustrates our vision for Wireless Visual Sensor Networks (WVSN) in Smart Grid, composed of several visual sensors interacting with networks of intelligent and multimodal sensors on one hand, and with cloud services on the other hand for storage and processing. Wireless visual sensors can learn key contextual inputs about users and environment to improve energy saving and sustainability. Different applications or usages may have subsets of this connectivity model. For example, in some safety-critical cases where delay may be very important, the smart devices and sensor networks may interact directly without cloud mediation. In other cases, the larger computational requirements may dictate an optimal split between smart devices and the cloud.

Benefits and Usage scenarios.

The expected benefits from WVSN in Smart Grid include simplicity and ease of use, context-sensitive and smart services allowing for more energy savings. The following examples (illustrated in Figure 2) show different usage scenarios for WVSN in Smart Grid for HEMS and energy savings in smart buildings and smart roads.

1) Home Energy Management System (HEMS): equipping smart houses to control energy consumption for automated energy control. WVSNs allow easy extraction of useful context information on the user presence and activity at home for automatic temperature and light settings Examples are: i) Detecting the presence of the user(s), putting off the heater (or air conditioner) and light if no user(s) is/are present at the room, gradual temperature and light setting. ii) Detecting the users' proximity to the

temperature/light source: optimizing temperature/light settings accordingly. iii) Detecting the user's location at home for optimizing the temperature/light setting: providing per room control, anticipating user's departure from home (if the user is moving to the door/garage of his house). iii) Detecting user's activity (busy, relaxing, reading, sleeping) and optimizing the ambient light level to the user's activity.

Depth cameras are useful in this scenario. In [3], depth cameras are used to analyze activity within the home which can give useful contextual information for energy management. Other sensors can be used to extract useful context information on the user. Examples are: i) location and motion sensors detecting the motion patterns of users to be able to detect if he is leaving the room/home. ii) outdoor location sensors "GPS on mobile devices" and mobility sensors detecting user's speed and sending user's location and speed to the Cloud that anticipates the user's distance from home and trigger the HEMS.

2)Smart Buildings and Offices: Similar energy management in buildings/offices. WVSN equipping buildings and offices can detect the presence and distribution of persons and employees to adjust light and temperature accordingly. Other sensors can exist with WVSN to extract useful context information and presence patterns for smart energy management.

3) Smart Road Lights Management: Smart management of street lights according to pedestrian presents, time of the day and vehicles density. WVSN allows easy extraction of context information on the presence pattern in roads for pedestrians and drivers. Examples are: i) Detecting presence of pedestrians, putting off the street lights if no pedestrians are present at their proximity. ii) Detecting pedestrians' motion direction/pattern and predicting the pedestrian's path, anticipating the street light to put on during the pedestrian path. iii) Detecting density of vehicles to optimize the street lights such that when the vehicles density is low, lesser street lights are put on. Other sensors (e.g. a badge/wearable sensor) can be used for more precision in detecting user's profile (e.g. old man, wheeled chairperson requiring specific light conditions).

Key requirements.

For efficient energy saving and intelligent data processing in Smart Grid, this section presents key requirements on sensors and data processing capabilities for visual sensors incorporating multimodal cases (where other type of sensors can be used).

- Sensors: Low power, low cost and small size.

- Contextualized localization: detecting user's location with appropriate details (e.g. detecting where the user is, including context such as "Home", "Living room", "kitchen"… etc.).

- Personalized identification: efficient and accurate user identification (knowing who the user is).

- Activity tracking: knowing user's activity in a detailed manner (is the user moving, lying down, sitting, reading, speaking on a phone, etc.).

- Group detection: Is it a single person or a group?

- Environment detection: Is there enough light? Is it a crowded place? Is it a noisy place?

- Privacy: Sensitive information preservation (Where is the user and with who? What are the surroundings like?).

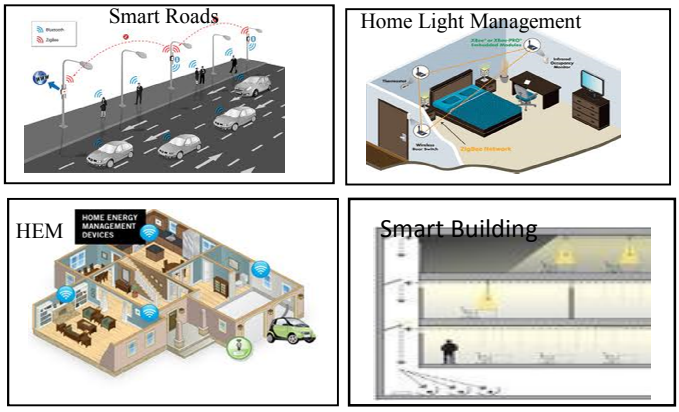

Fig 2. Usage Models for WVSN in Smart Grid

Architectural view.

We consider WVSN serving multiple applications in Smart Grid with multimodal sensors possibility for more reliable sensing and accurate profile precision for each user/application. In addition, each user can have different profiles according to each application needs and privacy level requirement. The architecture is composed of different layers (as shown in Figure 1) having the following details:

(i) Data collection phase: Visual sensors Multi-modal sensors (cameras at home, environment conditions sensor devices, wearable devices, sensors on smart phones, sensors in roads).

(ii) Data transfer phase: a) The raw data "sensed information" is sent either to a node in the local network (e.g. Home server or a user directly) or directly to the Cloud. b) The local network communication includes communication between sensors in a flat or hierarchal fashion (possibilities are multi-hop communication between sensors or a P2P communication allowing allows also to collect different pieces of data from different peers when more than one node is responsible for gathering the raw data).

(iii) Data Processing (locally or in the Cloud based on power and resources requirements): a) The raw data is

processed either by the local network and triggers an action to the user's service directly. b) The raw data is processed by the Cloud and triggers an action. c) The raw data is stored in the Cloud and processed by the local network through a query from the local network to the Cloud to fetch the necessary data on demand to process and trigger an action.

(iv) Context-aware Data Processing: Data processing is intelligent and done in a context-aware manner considering the context of the environment (light, noise, time of the day..) and the context of the user (user presence, proximity to certain places, ..).

Communication.

Communication between the sensors ranges from local communication to cloud communication:

(i) Local Communication: a) Communication between sensors, where an aggregation sensor node gathers information from multiple sensors (this can be a multi-hop communication between sensors or a P2P communication). b) Direct communication between each sensor and a centralized node at the user's sphere (Home server for example). c) Direct communication between a user and the sensor to enable some service.

(ii) Cloud Communication: the sensors transmit the sensed information to the Cloud either directly or through an aggregated sensor node or through a centralized node at the user sphere.

3. Technical challenges

Several technical challenges for WVSN applications in Smart Grids exist, which need efficient solutions. The following are some examples:

1) New paradigms for video coding & analysis:

- Trade off low power & complexity at sensor node for higher complexity at aggregation nodes (AN)/cloud.
- Distributed coding to exploit multiple sensor nodes.
- Deep integration between coding and video analysis through: i) optimal split of video analysis between sensor and AN and ii) pre-processing (partially) at node prior to coding.
- Coding performance evaluated by M2M application metrics: not necessarily human perception.

2) Communication between sensors & AN/cloud:

- Autonomously discover and configure best set of sensors for optimal application performance.
- Fusion of data from multiple sensors, adding robustness, also features such as depth.
- Cross-layer optimization for wireless communications combined with coded sensor data.

3) Sensor network architecture and protocols:

- 'Heterogeneous' sensors with multiple capability levels (power, complexity etc.).
- Local (p2p) vs. cloud-mediated connectivity.

For many of the WSVN applications with large numbers of video sensors, the system architecture should support more distributed processing closer to the edge. The optimal balance of processing between sensor node and the smart device and the cloud is a very important topic. Techniques such as distributed video coding (DVC) e.g. as in [5], multi-view video summarization, e.g. [6], distributed object detection and recognition, e.g. [7] are examples of how processing of visual information based upon distributed visual sensors can be exploited for delivering on the promise of Smart Grid with visual sensor nodes. An example of multimodal sensor integration including visual sensing in an ITS scenario is given in [4].

4. Summary and Conclusion

In this paper we presented some applications of WVSN in the emerging area of Smart Grid. Exploiting the advancements in multimodal wireless sensor technologies and the huge increase in smart applications enables creation of smart environments that interact with Smart Grid operations to provide users a superior experience. . Sensors provide key contextual inputs to learn more about users and environment aiming to improve robustness, reliability and better energy savings. The extraction, analysis and communication of these visual context cues will be increasingly enabled in low power SoCs, and can provide important information to complement and supplement information from other sensors.

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Distributed Direct Load Control for Large-Scale Residential Demand Response

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1. Introduction

Increasing electricity demand as well as an increase in electricity supply from intermittent renewable resources presents great challenges in matching supply and demand in power grids. Demand response (DR) techniques have proven to be a viable tool to tackle this challenge by introducing opportunities on the demand side [1]. In the residential scenario, many home appliances provide operational flexibilities which can be used as demand response resources to better match the supply and demand (e.g., GE Profile Brillion-enabled dishwasher and clothes washer/dryer [2]). However, in wide-area demand response systems with a large number of residential customers, a central challenge lies in determining how to manage these demand response resources effectively and with low computational and communication complexity so that operational flexibilities offered by certain kinds of loads can be fully exploited. Current residential demand response programs, e.g., direct load control (DLC) and pricing-based approaches, and existing research on demand response at the aggregated level have several issues to enable large-scale demand side participation [3].

Motivated by these challenges, this paper proposes a distributed direct load control approach for large-scale residential demand response. Our work contributes a two-layer communication-based control architecture to manage each individual demand response resource effectively and efficiently as a load shaping tool in real time. The lower-layer network is within each building, where the energy management controller (EMC) controls operation of appliances upon request according to a local power consumption target via wireless links. The upper-layer network consists of a number of EMCs in a region over which the demand is served by a load aggregator. The load aggregator wants the actual aggregated demand for this region to match a desired aggregated demand profile, to decrease the real-time deviation cost. The average consensus algorithm is employed to distributively allocate the desired aggregated demand among the serving buildings. The allocations determine each building's local power consumption target and the EMC in each building schedules appliance operations according to this target level. The overall result is an aggregated demand that closely matches the desired demand.

2. Two-layer communication-based control scheme

We consider a residential region with B building whose power consumption are served by a load aggregator. The set of buildings is denoted by $\mathcal{B}$. The two-layer communication-based distributed direct load control architecture is shown in Fig. 1, as the demand response of B buildings over this region.

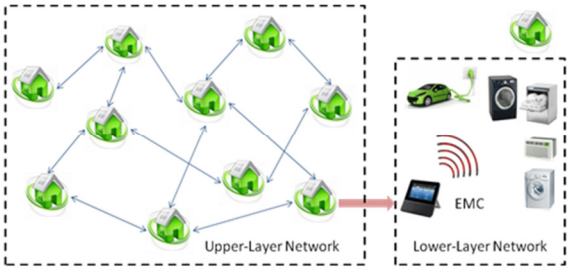

Fig. 1 Two-layer communication-based distributed direct load control architecture

The lower-layer network is within each building $i \in \mathcal{B}$, where an EMC is installed to locally schedule operation of appliances within the building via two-way wireless links between the EMC and appliances. Two types of appliances with operational flexibilities are considered as demand response resources in our scheme: a) *Type I flexible appliances* (denoted by the set $\mathcal{K}_i$) that are flexible in operation such that they can be switched on and/or off either when requested or possibly some time later, e.g., clothes washer/dryer and dishwasher. b) *Type II flexible appliances* (denoted by the set $\mathcal{Z}_i$) that provides flexibilities that their power consumptions can be altered, e.g., the plug-in electric vehicle (PEV) whose battery charging rate can be adjusted as long as the charging is completed before the departure [4].

The upper-layer network consists of EMCs of the buildings in the region. This EMC network is designed without a central controller, i.e., each EMC only communicates to its neighboring EMCs. We assume that each pair of EMCs with a direct link have two-way communication capability, and the EMC network is strongly connected, i.e., no island exists in the network. This assumption is consistent with the smart grid communication network implemented in practice, e.g., the Smart Grid Infrastructure provided by Silver Spring Networks [5].

The load aggregator serving this region has a desired demand Z_τ for each frame τ, which can be the optimal day-ahead (real-time) cleared responsive demand bid that the load aggregator submitted into the wholesale electricity market for each frame τ, or the optimal aggregated responsive demand in the social welfare maximization problem in the work of [6] and [7]. In real-time operations, the upper-layer network coordinates the EMCs such that the actual aggregated demand of the buildings over this region to be lower than Z_τ, i.e., the actual demand always fulfills the demand commitment in advance, and the actual aggregated demand should be as close to this Z_τ as possible to minimize the deviation cost.

The main idea underlying the proposed approach is to allocate the desired demand value Z_τ to each EMC as a local power consumption target, denoted by θ_i^τ, via coordination among EMCs utilizing the upper-layer network. This target is used by the EMC to control appliance operations within the building exploiting the lower-layer network. Thus, by local appliance control according to θ_i^τ, the actual aggregated demand can approach the target Z_τ. To do this, we design the frame-based protocol to integrate the two-layer modules of communication and control in the EMC, as shown in Fig. 3. Each frame has three phases:

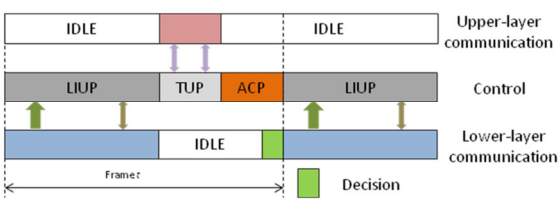

Fig. 2 Two-layer communication and control protocol

1) Load Information Update Phase (LIUP): During the LIUP, the EMC lower-layer communication interface module receives the power request information from appliances in the building. Specifically, for Type I flexible appliances, the power request information refers to the power-on or power-off request of $P_{i,j}^\tau$ for appliance j in building i during frame τ. For Type II flexible appliances, the power request information refers to the bounds of power consumption, denoted by $v_{i,j}^{\tau,\min}$ and $v_{i,j}^{\tau,\max}$, that specify the range within which the appliance may consume. With this data collected, the control module updates the aggregated fixed load in the building, denoted by $\hat{q}_i^\tau$, as the demand that must be satisfied, and the aggregated flexible load in the building, denoted by $\tilde{q}_i^\tau$, as the demand that can be altered, respectively.

2) Target Update Phase (TUP): During the TUP, with the $\hat{q}_i^\tau$ and $\tilde{q}_i^\tau$ obtained in LIUP, the upper-layer communication interface module at each EMC communicates with its neighboring EMCs to compute the local demand target value θ_i^τ for the frame τ. We employ the average consensus algorithm as the coordination among the EMCs to distributively allocate the desired demand to each local target θ_i^τ.

3) Admission Control Phase (ACP): During the ACP, the EMC's control module makes the admission decision, i.e., decides which Type I flexible appliances can be turned on and power consumptions of type II flexible appliances, given the local demand target value θ_i^τ. At the end of the ACP, the lower layer communication interface module broadcasts the admission decision and synchronizes to the next frame.

3. Distributed demand target allocation in upper-layer EMC network

The local demand target θ_i^τ should reflect the aggregated demand and supply status specified by $\sum_{i\in\mathcal{B}}\hat{q}_i^\tau$, $\sum_{i\in\mathcal{B}}\tilde{q}_i^\tau$, and Z_τ. To do so, we design the ratio η_τ as the ratio of the total demand target gap, $Z_\tau - \sum_{i\in\mathcal{B}}\hat{q}_i^\tau$, to the total demand from flexible appliances, $\sum_{i\in\mathcal{B}}\tilde{q}_i^\tau$, i.e.,

$$\eta_\tau = \frac{Z_\tau - \sum_{i\in\mathcal{B}}\hat{q}_i^\tau}{\sum_{i\in\mathcal{B}}\tilde{q}_i^\tau}, \quad (1)$$

And the EMC for building i applies this ratio η_τ to set its local target power consumption, θ_i^τ, as

$$\theta_i^\tau = \hat{q}_i^\tau + \eta_\tau \cdot \tilde{q}_i^\tau. \quad (2)$$

If each EMC controls power requests of appliances at frame to follow this target value θ_i^τ, then we can verify that $\sum_{i\in\mathcal{B}}\theta_i^\tau = \sum_{i\in\mathcal{B}}\hat{q}_i^\tau + \eta_\tau\sum_{i\in\mathcal{B}}\tilde{q}_i^\tau = Z_\tau$, i.e., the aggregated target demand matches the desired demand Z_τ for time τ. Depending on the values of θ_τ, three scenarios are discussed which can be found in [3].

To allocate the target values for EMCs in a distributed way, the average consensus algorithm [8] [9] is applied for the information exchange of neighboring EMCs using the upper-layer EMC network. Specifically, let $\hat{Q}_i^\tau(k)$ and $\tilde{Q}_i^\tau(k)$ denote the iteration variables at the step k, and their initial values are set as $\hat{Q}_i^\tau(0) = \hat{q}_i^\tau$ and $\tilde{Q}_i^\tau(0) = \tilde{q}_i^\tau$. By iteratively linear updates as

$$\hat{Q}_i^\tau(k+1) = \hat{Q}_i^\tau(k) + \varepsilon \cdot \sum_{j\in\mathcal{N}_i}\left[\hat{Q}_j^\tau(k) - \hat{Q}_i^\tau(k)\right] \quad (3)$$

$$\tilde{Q}_i^\tau(k+1) = \tilde{Q}_i^\tau(k) + \varepsilon \cdot \sum_{j\in\mathcal{N}_i}\left[\tilde{Q}_j^\tau(k) - \tilde{Q}_i^\tau(k)\right], \quad (4)$$

the values of $\hat{Q}_i^\tau(k)$ and $\tilde{Q}_i^\tau(k)$ will converge to the average value $\hat{q} = 1/B\sum_{i\in\mathcal{B}}\hat{q}_i^\tau$ and $\tilde{q} = 1/B\sum_{i\in\mathcal{B}}\tilde{q}_i^\tau$, respectively, with a proper step size ε. The $\mathcal{N}_i$ denotes the set of neighbors of the EMC i in

the upper-layer network. After the updates converge, the global ratio η_τ can be computed locally at each EMC level as $\eta_\tau = Z_\tau - B \cdot \hat{q}^{\tau *} / B \cdot \tilde{q}^{\tau *}$. The details of convergence results as well as the design of the step size ε can be found in [3] and references therein.

4. Lower-layer communication and admission control scheme

In the lower-layer network, the flexible appliances send power on/off request packets to the EMC, and the EMC update the $\hat{q}_i^\tau$ and $\tilde{q}_i^\tau$ during LIUP phase accordingly. We define the essential fields of the request packet for our proposed approach in [3]. During the ACP phase, the EMC makes admission decision on which flexible appliances to turn on and adjusts the power consumptions, according to the local demand target value θ_i^τ . A mixed-integer linear programming problem is formulated for the admission control of the EMC. The non-intrusive operations for appliances (including the customer override option, preventing frequent ON/OFF switching, and Operation deadline) are also integrated in our approach. Details of these parts can be found in our full paper [3].

5. Conclusion

In this paper, an innovative two-layer communication-based distributed direct load control approach is proposed for large-scale residential demand response. We employ average consensus algorithms in the upper layer network to allocate target power consumption levels for each building. The EMC in each building then schedules appliance operations according to the local power consumption target. The protocol integrates these two layers seamlessly and also enables non-intrusive operation of appliances.

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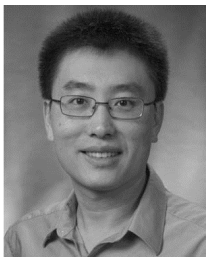

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Last-Mile Communication Solutions for China Southern Power Grid

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I. Introduction

Power distribution network is the crucial platform for the convergence of power flows, data flows, and service flows in smart power grid. Distribution networks is able to provide comprehensive operational information for distribution synthetically analysis and effective decision-making. However, the development of power distribution networks is largely behind the development of transmission networks (above 35 kilovolt), especially in China. The main reasons include: 1) insufficient investments due to the traditional argument "emphasizing power generation and transmission rather than power distribution"; and 2) the challenges of massive number of terminals in diverse environments.

The electrical power grid is typically separated logically into transmission systems and distribution systems. Electric power transmission systems typically operate above 110 kilovolt, whereas distribution systems operate at lower voltages (10 kilovolt or below). Recently the demands for reliable distribution network are growing rapidly. In the smart grid, the emerging solar/wind energy infrastructure and new electronic vehicles may feedback the electric energy, making the bidirectional energy flow feasible. The bidirectional data flow enables effective electric data exchange for intelligent power scheduling. Besides, there are more requests for prompt fault location, real-time line/equipment status feedback and maintenance cost saving. As the basis for intelligent scheduling, the last-mile communication in distribution systems has become the bottleneck for tremendous data collections and real-time controls. Some advanced technologies have been proposed in the literature [1]-[4].

Dedicated wireless broadband network is regarded as a potential solution for massive data collections and real-time downlink controls in power distribution networks in China. In the rest of this letter, we will discuss the motivation, trial projects in China southern power grid, and the practical challenges.

II. Communication Requirements

Extensive last-mile access is motivated by the power distribution networks. Nevertheless, the applications available on this access platform are very different. There are mainly three types of services.

1) Distribution Automation: intends for power grid optimization and prompt fault recovery by monitoring the status of substation, pole top breaker, line fault indicator, line capacitor, and voltage regulator. This type of service includes supervisory control and data acquisition (SCADA), feeder automation (FA), and senior distribution network analysis. In addition, tele-signal, tele-measuring, and tele-control are three common terminologies for function distinction. Furthermore, video monitoring of electric power pylons and related facilities is taken into account.

2) Metering Automation: performs real-time data collection of tremendous metering terminals. Generally, this type of services can be classified into three portions: load management (10 kilovolt dedicated distribution transformer), distribution transformer monitoring (10 kilovolt public distribution transformer), and low volt metering (380/220 volt consumer ammeter).

3) Intelligent Electricity Consumption: It evolves with the development of emerging energy resources and applications. Currently, smart homing, electric vehicle (EV) charging pile, family distributed energy are potential services in the smart grid. Bidirectional communication link plays an important role for these innovative applications.

Different services have different requirements on the communications and information delivery. We show the communication requirements for these services in Table 1.

Table 1 Communication QoS Requirements

Service Type		CPE/UE Bandwidth	Latency Requirement
Distribution Automation	tele-signal	1K bps	5s
	tele-measuring	5K bps	5s
	tele-control	1K bps	1s
Metering Automation		1K bps	10s
Video Monitoring		2M bps	500ms

In China southern power grid (CSG), power distribution and metering automation are now focusing on the initial stage of distribution network construction. Currently, video monitoring and new resource access are still optional. Therefore, the communication requirement now is the secure real-time access of tremendous terminals with rate below 10Kbps in a cost-effective manner.

III. Progress in China Southern Power Grid(CSG)

Fig.1 shows the last-mile communication network topology in China. Most distribution/metering automation data can be gathered by dedicated wireless cellular network, while fiber communication intends for crucial spots/users and rented public cellular network for other metering terminals in outage. Compared with several communication schemes available (i.e., optical fiber, power line communication, rented cellular network and dedicated wireless cellular network), dedicated wireless cellular networks has been regarded as a highly promising solution for the smart grid development in China.

In CSG, several trial projects of dedicated wireless cellular networks are ongoing in the cities of Guangzhou, Shenzhen, Zhuhai, Dongguan, Zunyi, and Guiyang.

The first phase of trial project in Zhuhai with 10 dedicated base stations has been completed in 2012. Since this first attempt of TD-LTE based dedicated network for smart grid in China, the demonstration has attracted over twenty visiting groups from all over the world, such as Electricite De France, State Power Corporation of Thailand, and China Light & Power Co. Ltd.

The base stations are deployed in the sites belonging to local power supply station (such as substations and administrative buildings) with the target of best-effort coverage rather than seamless coverage in public counterpart. The nodes in outage can be connected by fiber or rented public network in a complementary way. Also, the core network facilities are deployed in the existing communication center or main control center, gathering the data from all base stations via the existing fiber transmission networks. Because all these sites are private, the site lease charges can be saved and the installation, operation and maintenance are more convenient.

Customer premises equipment (CPE) and feedback modules are two major terminals for distribution networks. CPEs are used for both uplink and downlink, while the feedback modules are only for uplink data collection. In CSG, feedback modules have small size and can be easily deployed. These modules are used for a large number of smart meters data gathering.

Among many wireless technologies, TD-LTE (in 1785 -1805MHz band) and LTE230 (discrete frequency points around 230MHz) are adopted in the trial projects of CSG. We have considered technical challenges, local frequency policy, and industrial chain to choose these two technologies.

IV. Practical Challenges in CSG

We take the trail project in Zhuhai as an example. There are 8 base stations cover about 25% of the central district of Zhuhai city with coverage radius 1.5-2.5km for rural and 1km for urban. Based on TD-LTE technology in bandwidth (1790-1795MHz), the online rates of current services are 100% with the latency below 200ms, even in the period of 'West' typhoon with maximum winds of up to force 8 (July 2012). The stable and reliable operations in trail projects demonstrate the feasibility and effectiveness of our developed dedicated wireless networks for smart grid.

With the progress of dedicated wireless cellular networks, some new and practical challenges appear.

1) *Frequency Uncertainty*: 1.8GHz (5MHz bandwidth) and 230MHz (1MHz bandwidth) are two possible ranges of frequency for the dedicated networks in China. Originally, the portions of bandwidth around 230MHz have been assigned for data transmission radio in the electric industry by the state radio regulation center of China. The other adjacent bands belong to other industries and applications. To avoid the frequency band license confliction, the original bands have been assigned to State Grid Corporation of China since 2013. However, a special carrier aggregation (the unit is 25KHz) has to be employed to bear more services. The band license around 1.8GHz is only used in the trial demonstration but not officially assigned yet. This may incur risk in the phase of large-scale development. The reason is that there are only 5MHz of 1785-1805 MHz available to prevent mutual interferences of the adjacent band systems (5MHz guard band for each side). This very limited guard band may not be efficient in spectrum utilization.

2) *Technologies Choice*: China Potevio Co., Ltd developed LTE230 for the smart grid in 40 frequency points (each occupies 25KHz around 230MHz), while TD-LTE (in 1785-1805 MHz) follows the 3GPP standard supported by Huawei, ZTE, Ericsson. Compared to TD-LTE, LTE230 has wider coverage area, (LTE230: 5-8km radius, 1.8G TD-LTE: 1-3 km radius) making the network deployment much cheaper. The drawback of LTE230 is the bandwidth limitation (licensed discrete 1MHz band), which is not sufficient for future video applications. In CSG, trail projects based on both technologies are on the way.

3) *Wireless Security Consideration*: Information security protection is a crucial issue in smart grid [5][6]. The eavesdropping or falsification of key control signals will lead to catastrophic widespread blackouts. Compared with the wire communication, the signals in the free space pose security challenges and decision-maker's uncertainty on the progress of large-scale promotion, although the security techniques are sufficient to some extent.

4) *Economic Effective Coverage*: The sites are limited to the substations or administrative buildings. Hence there are uncovered areas. Moreover, some nodes are located in the basement suffering from

serious wall penetration loss or shadowing loss. The straightforward solution for complementary coverage is to extend the antenna to outdoor, which is however difficult in some scenarios. Relay or small-cell base station may work well at the cost of investment for one single terminal. The power supply of these relays is still a problem. Thus, there are no well-developed approaches available for complementary coverage in dedicated networks.

V. Conclusion

This letter introduces the main challenges and solutions related to the dedicated wireless cellular networks for last-mile access in the smart power grid, on basis of the trial projects in CSG.

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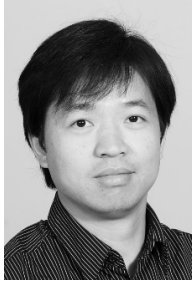

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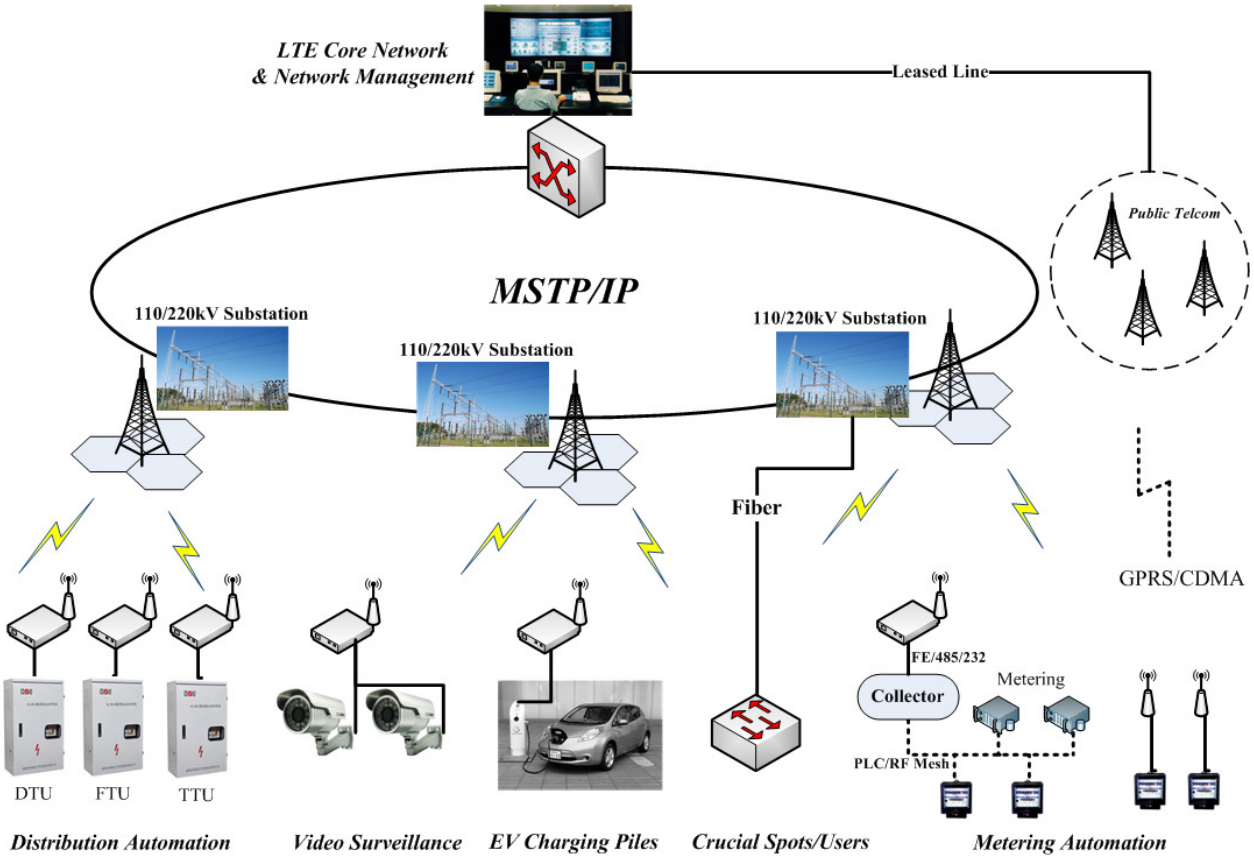

Fig. 1 Last-Mile Communication Network Topology for Smart Grid in China

Asymptotic Optimal Online Energy Distribution in the Smart Grid

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1. Introduction

A smart grid is an electrical grid that is enhanced with communications and networking, computing, and signal processing technologies [1,2]. The two-way energy and information flows, along with the smart devices, bring about new perspectives to energy management and demand response in the smart grid.

Demand side management is one of the most important problems in smart grid research, which aims to match electricity demand to supply for enhanced energy efficiency and demand profile while considering user utility, cost and price [1]. Researchers have been focusing on peak shifting or peak reduction for reducing the grid deployment and operational cost [3], [4], as well as on reducing user or energy provider's cost [5], [6]. In particular, some prior works aim to achieve a single objective, such as to improve the users' utility or reduce the cost of the energy provider [7], while others jointly consider both the user and energy provider costs, to increase the users' utility as much as possible while keeping the energy provider's cost at a relatively lower level [8]. Given the wide range of smart grid models and the challenge in characterizing the electricity demand and supply processes and the utility, cost, pricing functions, a general model that can accommodate various application scenarios would be highly desirable. Furthermore, it is important to jointly consider the utilities and costs of the key components of the system to achieve optimized performance for the overall smart grid system.

We consider real-time energy distribution in a smart grid system. As shown in Fig. 1, the distribution control center (DCC) collects real-time information from the three key components, i.e., the users, the grid, and the energy provider, makes decisions on, e.g., electricity distribution, and then sends the decisions back to the key components to control their operations. The smart meters at the user side will be responsible for the information exchange with the DCC and for enforcing the electricity schedule received from the DCC. The information flows are carried through a network infrastructure, such as a wireless network or a powerline communication system [1].

For optimizing the performance of such a complex network system, the utilities and costs of the three key components, i.e., the users, the grid, and the energy provider, should be jointly considered. In this paper, we take a holistic approach, to incorporate the key design factors including user's utility and cost, grid load smoothing, dynamic pricing, and energy provisioning cost in a problem formulation. To solve the real-time energy distribution problem, we first present an offline algorithm that can produce optimal solutions but assuming that the future user and grid information are known in advance. Based on the offline algorithm, we then develop an online algorithm that does not require any future information. As the name suggests, an online algorithm operates in an online setting, where the complete input is not known *a priori* [9]. It is very useful for solving problems with uncertainties. We find the online algorithm particularly suitable in addressing the lack of accurate mathematical models and the lack of future information for electricity demand and supply in this problem. We also prove that the online algorithm converges to the optimal offline algorithm almost surely.

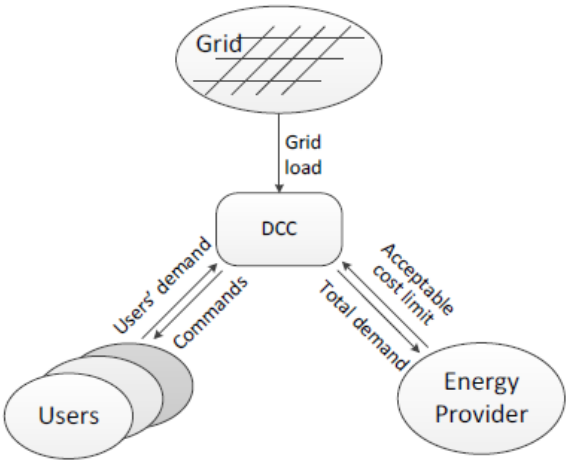

Fig. 1. Illustration of the key elements and interactions in the smart grid.

The proposed framework is quite general. It does not require any specific models for the electricity demand and supply processes, and only have some mild assumptions on the utility, cost, and price functions (e.g., convex and differentiable). The proposed algorithm can thus be applied to many different scenarios. The online algorithm also does not require any future information, making it easy to be implemented in a real smart grid system. It is also asymptotically optimal, a highly desirable property.

The proposed algorithm is evaluated with trace-driven simulation using energy consumption traces recorded in the field. It outperforms a benchmark scheme that assumes global information.

2. Problem Statement and Main Results

We aim to minimize the load variance in the grid while maximizing user satisfaction. Large load variance is undesirable for grid operation. It brings about uncertainties that affect not only user satisfaction but also the stability of the power system. Furthermore, the energy provisioning cost should be bounded and users' necessary power needs should be guaranteed.

We first consider an offline scenario where the DCC distributes the power to users during time $t = [1, 2, \cdots, T]$, and all the information on users' flexibility $\omega_i(t)$ and provider's budget $c(t)$ are assumed to be known in advance. Let $P_i(t)$ denote the power usage for user i at time t. In this paper, we use upper case P in the *offline problem*, where all the necessary constraints are known *a priori*. In the corresponding *online problem*, we use lower case p for the corresponding variables. A vector with subscript i is used to denote a time sequence, e.g., $\vec{P}_i$ for the power usage by user i for $t = \{1, 2, \cdots, T\}$. The offline problem Prob-OFF can be formulated as follows.

$$\max: \sum_{t=1}^{T}\sum_{i\in\mathbb{N}}\left[U(P_i(t),\omega_i(t)) - f\left(\sum_{i\in\mathbb{N}} P_i(t)\right)P_i(t)\right] - \frac{\alpha T}{2}\mathrm{Var}\left(\sum_{i\in\mathbb{N}}\vec{P}_i\right) \quad (1)$$

subject to:

$$P_i(t) \geq P_{i,min}(t), \forall\, i \in \mathbb{N}, t \in \{1, 2, \cdots, T\} \quad (2)$$

$$C\left(\sum_{i\in\mathbb{N}} P_i(t)\right) \leq c(t), \forall\, t \in \{1, 2, \cdots, T\}, \quad (3)$$

where Var(·) is the variance of the total power, $U(\cdot)$ is the user utility function, $f(\cdot)$ is the price function, α is a nonnegative parameter to trade-off between user satisfaction and grid load variance, $p_{i,min}(t)$ is user i's minimum demand at time t, $C(\cdot)$ is the energy provisioning cost function. See [11] for details.

We show that Prob-OFF is a convex problem, as given in the following Lemma.

Lemma 1. *Prob-OFF is a convex optimization problem and has a unique solution.*

We next develop an online algorithm for energy distribution, and prove that the online solution is asymptotically convergent to the offline optimal solution, i.e., asymptotically optimal. The online energy distribution algorithm consists of the following three steps.

Step 1: For each $i \in \mathbb{N}$, initialize $\hat{p}_i(0) \in \mathbb{P}$.
Step 2: In each time slot t, the DCC solves the following convex optimization problem (termed Prob-ON).

$$\max: \sum_{i\in\mathbb{N}} U(p_i(t),\omega_i(t)) - f\left(\sum_{i\in\mathbb{N}} p_i(t)\right)\sum_{i\in\mathbb{N}} p_i(t) - \frac{\alpha}{2}\sum_{i\in\mathbb{N}}(p_i(t) - \hat{p}_i(t-1))^2 \quad (4)$$

$$\text{subject to: } p_i(t) \geq p_{i,min}(t), \forall\, i \in \mathbb{N} \quad (5)$$

$$C\left(\sum_{i\in\mathbb{N}} p_i(t)\right) \leq c(t), \forall\, t. \quad (6)$$

Let $\vec{p}^*(t)$ denote the solution to Prob-ON, where each element $p_i^*(t)$ represents the optimal power allocation to user i.
Step 3: Update $\hat{p}_i(t)$ for all $i \in \mathbb{N}$ as follows.

$$\hat{p}_i(t) = \hat{p}_i(t-1) + \frac{\alpha}{t+\alpha}\cdot(p_i^*(t) - \hat{p}_i(t-1)). \quad (7)$$

Similar to Prob-OFF, problem Prob-ON is also a convex optimization problem satisfying Slater's condition. We have the following theorem. Please see [11] for a detailed proof.

Theorem 1. *The online optimal solution converges asymptotically and almost surely to the offline optimal solution.*

3. Performance Evaluation

We evaluate the proposed online algorithm with trace-driven simulations. The simulation data and parameters are acquired from the traces of power consumption in the Southern California Edison (SCE) area recorded in 2011 [10]. We compare the online algorithm with the Optimal Real-time Pricing Algorithm (ORPA) presented in [8] as a Benchmark.

The total power consumption of the different algorithms are plotted in Fig. 2. From the aspect of smoothness, we could see clearly that the online optimal real-time energy distribution algorithm with α=1 (termed OORA(1)) achieves the best performance. The figure also shows that the online algorithm with α=0.01 (termed OORA(0.01)) also outperforms the benchmark ORPA. All the three algorithms achieve smoother total loads than the real consumption (RC). The peak reductions over RC are 35% for OORA(1), 28% for OORA(0.01), and 12.5% for ORPA. Therefore, OORA(1) achieves the largest peak reduction, while OORA(0.01) still outperforms ORPA with

considerable gains. Please check out [11] for more simulation results and discussions.

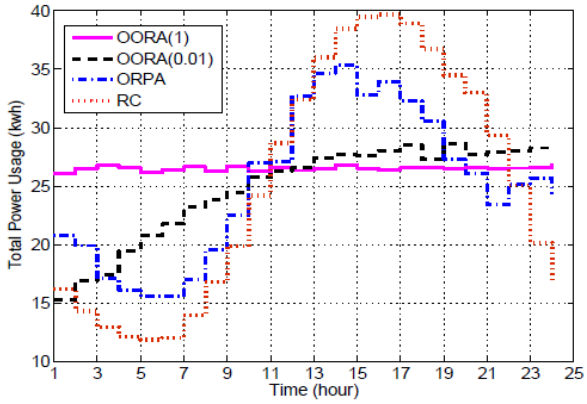

Fig. 2. Total power consumption for OORA(1), OORA(0.01), ORPA and RC.

4. Conclusion

In this paper, we present a study of optimal real-time energy distribution in smart grid. With a formulation that captures the key design factors of the system, we first present an offline algorithm that can solve the problem with optimal solutions. We then develop an online algorithm that requires no future information about users and the grid. We also show that the online solution converges to the offline optimal solution asymptotically and almost surely. The proposed online algorithm is evaluated with trace-driven simulations.

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