Key Performance Aspects of an LTE FDD based Smart Grid Communications Network

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Agenda

- **Introduction**
  - Applications & Role of Communications in Smart Grid
  - Key performance issues – MAC latency and channel utilization
  - Contributions

- **Overview of LTE-Standard Systems**
  - Network Architecture (layered)
  - Access technology
  - Dynamic Scheduling and Transmission Time Interval (TTI)
  - Hybrid ARQ

- **Theoretical Analysis**
  - Latency
  - Channel Utilization

- **Simulation Results**

- **Conclusions**
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Introduction

Smart Grid

- New factors: market deregulation, distributed power generation, new load types (plug-in EVs) and etc.
- Potential Applications
  1. Advanced Metering Infrastructure (AMI)
  2. Demand Response
  3. Wide Area Measurement Systems (WAMS) - Phasor Measurement Units (PMUs)
- Much more uplink transmissions than downlink (uplink biased)

Role of Communications in Smart Grid

- Act as an enabling technology allowing info exchange among different entities
- Traffic Type: relatively large number of devices sending relatively small size packets with real-time effective payload
- Layered Deployment:
  1. Low range: low range sensor networks (IEEE 802.15.14 or Zigbee)
  2. Medium Range: Field Area networks (FANs) based on 802.11
  3. Wide Area: Wide Area Networks (WANs) based on LTE or WiMAX
- Why LTE
  - Large Coverage, high spectral utilization, centralized control for security and QoS provisioning
Introduction

LTE

- Proposed by 3GPP, Release 8, Frequency Division Duplex (FDD)
- Key Parameters in Smart Grid – Latency and channel utilization
  1. Latency: monitoring and control → stability based on detecting and acting on anomalies
  2. Channel utilization: uplink biased applications (e.g., WAMS), which channel is more likely to be blocked or saturated first

Contributions

- Develop a mathematical formulation for uplink latency
  1. Give through both analysis and simulation the minimum uplink latency for typical Smart Grid traffic sources in an LTE FDD network.
  2. Show how the latency varies with the number of PMUs and packet size (payload)
- Mathematical formula for channel utilization
  1. PDCCH (Physical downlink control channel) channel utilization
  2. Show the capacity of an LTE FDD is PDCCH control channel limited when many devices send small sized packets
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Overview of LTE FDD Systems

LTE

- UMTS
  - 3G Universal Mobile Telecommunication System
- LTE Re8
- LTE-A Re10
  - 4G Long Term Evolution - Advanced System

Features

- Higher data rates – 300Mbps for downlink and 75Mbps for uplink
- Lower latency (connection set up and data transfer)
- Higher spectrum efficiency
Overview of LTE FDD Systems

- **Network Architecture**

  - **eNodeB**: Enhanced base station integrated all the functionalities of RNC (Radio network controller)
  - **PDCP**: Packet data convergence protocol
  - **RRC**: Radio Resource Control
  - **RLC**: Radio link control
  - **Hybrid ARQ**: Automatic repeat request combining backward and forward error correction
  - **PDCCH**: Physical downlink control channel
  - **CQI**: Channel quality indicator
Overview of LTE FDD Systems

Access Technology

- **Physical Resource Blocks (PRB):** composed of 12 consecutive subcarriers (12KHz)
- **Minimum resource allocation unit:** user can be assigned with one or more PRBs
- **OFDMA for downlink and SC-OFDMA for uplink**
Overview of LTE FDD Systems

- **Dynamic Scheduling**
  
  **Downlink**
  - Transmission Time Interval (TTI): 1 Frame (10ms) divided into 10 sub-frames (1ms), facilitates lower data latency since data can be sent in a smaller transmission interval
  - Scheduled every sub-frame on PDSCH and PUSCH between various users
  - Variability in time domain and frequency domain
  - Scheduling is special in Smart Grid: monitoring, control and protection traffic, small packets with strict latency requirement

**4 Channels:** PDCCH (Physical downlink control channel), PUCCH (Physical uplink control channel), PDSCH (Physical downlink shared channel), PUSCH (Physical uplink shared channel)

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Overview of LTE FDD Systems

- Hybrid ARQ
  - Different from ARQ in RLC layer, takes place in MAC layer
  - Contain a different set of redundancy bits for forward error correction
  - Remains the previous wrongly decoded packet for combined decoding
  - Combines forward + backward error correction
  - Round Trip Time: 8 TTIs
  - Double-edged sword: error free for monitoring data and control commands, but retransmissions enlarge the latency
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Theoretical Analysis - Latency

Latency

- Basic latency is 1ms
- In practice, there are other latency sources

(a) Downlink

1. Data for UE enters eNodeB TX buffer
2. UE wakes from DRX operation but the eNodeB does not schedule downlink frame for UE
3. UE wakes from DRX operation and the eNodeB sends data to the UE on the PDSCH and data associated signalling on the PDCCH

- DRX: discontinuous reception for power saving, listens to the channel periodically and sleep in between. Improve the battery life at the expense of increased latency
Latency

(b) Uplink

• **SR**: Scheduling request on the PUCCH, sent at periodic intervals and assigned an offset within SR tx period
• **BSR**: Buffer state report, indicating the volume and priority
Theoretical Analysis - Latency

Latency

- Other sources: retransmissions, packet splitting into fragments, state transition (RRC_connected, RRC_IDLE)
- Concentrate on LTE uplink with small packet size
- \( T_{\text{UPLINK}} = U_1 + U_2 + 4 + 8N_{\text{RE-TRANSMISSIONS}} \)
- \( U_1 \) – The number of TTIs to the next SR tx opportunity
- \( U_2 \) – The number of TTIs taken to get the uplink tx grant from eNB
- Conditions for this equation
  1. Small packet size that can be finished within one TTI
  2. In RRC_CONNECTED mode
  3. The device has not been assigned a uplink tx grant before
- Best case: 6ms
Theoretical Analysis - Latency

- Latency
  - For medium size packets (Best Case)

![Diagram of Medium size packet](image-url)
Theoretical Analysis - Latency

Latency

- For large size packets (Best Case)

(c) Large packet

1. Data packet enters UE TX buffer
2. UE sends Scheduling Request (SR) to eNodeB during its specific SR opportunity on the PUCCH
3. eNodeB sends an initial uplink grant on the PDCCH for 584 bits on 1, 2, 3 or 4 RB pairs. The grant applies to 4 sub-frames in the future.
4. UE sends Buffer Status Report (BSR) and part of the data packet to the eNodeB on the PUSCH
5. eNodeB sends a 2nd uplink grant on the PDCCH for part of the remaining data bits (as indicated in the BSR). The grant applies to 4 sub-frames in the future.
6. eNodeB sends a 3rd uplink grant on the PDCCH for the remaining data bits (as indicated in the BSR). The grant applies to 4 sub-frames in the future.
7. UE sends data to the eNodeB on the PUSCH
8. UE sends remaining data to the eNodeB on the PUSCH

Sub-frame

n n+1 n+2 n+3 n+4 n+5 n+6 n+7 n+8 n+9 n+10 n+11 n+12

12 ms
Theoretical Analysis – Channel Utilization

Channel utilization
- Smart Grid Traffic: small packets sent infrequently
- LTE is designed originally for voice and bursty traffic
- Concentrate on PDCCH
- 1 TTI is divided into 14 symbols among which 1-3 symbols are allocated for control signaling
- Resource elements
Theoretical Analysis – Channel Utilization

Channel utilization

\[ N_{RE}^{PDCCH} = N_{SC}^{RB} N_{RB}^{DL} N_{SYMBOLS}^{PDCCH} - (N_{RE}^{PDCCH} + N_{RE}^{PHICH} + N_{CS-RS}^{RE}) \]

- \( N_{SYMBOLS}^{PDCCH} \) is the number of symbols assigned to PDCCH
- PCFICH and PHICH are other control channels sharing the same resources with PDCCH
- \( N_{CS-RS}^{RE} \) is the number of cell specific reference signals for channel measure

\[
\begin{align*}
\max(N_{RE}^{PDCCH}) &= 36N_{RB}^{DL} - (16 + 12N_{GROUPS}^{PHICH} + 2N_{RB}^{DL}) \\
&= 34N_{RB}^{DL} - (16 + 12N_{GROUPS}^{PHICH}) \\
\max(N_{CCE}^{PDCCH}) &= \max(N_{USERS}) = \frac{34N_{RB}^{DL} - (16 + 12N_{GROUPS}^{PHICH})}{36}
\end{align*}
\]

It follows from (4) that:

\[ \max(N_{USERS}) < N_{RB}^{DL} \]
Theoretical Analysis – Channel Utilization

- Channel utilization

\[
\max(N_{CCE}^{PDCH}) = \max(N_{\text{USERS}}) = \frac{34N_{RB}^{DL} - (16 + 12N_{\text{GROUPS}}^{PHICH})}{36}
\]

It follows from (4) that:

\[
\max(N_{\text{USERS}}) < N_{RB}^{DL}
\]

- Conclusion: The capacity of LTE FDD system is control channel limited when the users have small size packets to transmit
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Theoretical Analysis – Simulations

Simulation Set Up

- Simulate a network of PMUs using an LTE FDD system
- Each PMU measures and reports the WAMS periodically
- All PMUs are synchronized
- To be more realistic: A relative small amount of downlink control traffic with exponential inter-arrival times are sent in PDCCH
- Uplink packet structure

```
<table>
<thead>
<tr>
<th>LTE MAC, RLC and PDCP headers</th>
<th>IPv4 header</th>
<th>UDP header</th>
<th>Payload (IEEE C37.118 Packet)</th>
</tr>
</thead>
</table>
```

- variable
- 20 bytes
- 8 bytes
- variable

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Theoretical Analysis – Simulations

- Simulation Results
  - Mean latency as a function of load (payload size 32bytes)

- Observations
  1. The best case uplink latency is very close to 6ms
  2. Latency decreases as the channel bandwidth increases
  3. Latency increases as the number of PMUs increases
  4. Downlink latency remains almost the same
Simulation Results

• Mean channel utilization as a function of load (payload size 32bytes)

• Observations
  The channel utilization of PDCCH is higher than that of PUSCH under the same amount of PMUs → Control channel will be saturated earlier → control channel limited capacity
Theoretical Analysis – Simulations

Simulation Results

- Mean latency as a function of packet size (fixed number of PMUs)

- Observations
  1. Sharp jumps by at least 5ms at 40 Bytes
  2. Less sharp jumps by at least 1ms at 130 Bytes
Theoretical Analysis – Simulations

Simulation Results

• Mean channel utilization as a function of packet size (fixed number of PMUs)

• Observations
  1. Sharp jumps
  2. Utilization of PUSCH is smaller than that of PDCCH in small packet size, but crossing points occur when packet size continue to increases
Conclusions

- Analyze the key performance – latency and channel utilization of LTE to be used in smart grid environment

- Study the best case latency for smart grid traffic

- Propose mathematical formulation for channel utilization and demonstrate that the capacity of LTE FDD system is control channel limited in Smart Grid scenario

- Extensive simulations validate the theoretical analysis