Can LTE-A Support Real-Time Smart Meter Traffic in the Smart Grid?[1]

Elias Yaacoub

Abstract

This chapter investigates the real-time reading of smart meter information in dense deployments of smart meters under a smart grid paradigm. The chapter investigates the scheduling load added on a long term evolution (LTE) and/or LTE-Advanced (LTE-A) network when automatic meter reading (AMR) in advanced metering infrastructures (AMI) is performed using internet of things (IoT) deployments of smart meters in the smart grid.

First, radio resource management algorithms to perform dynamic scheduling of the meter transmissions are proposed and investigated. It can be shown, through Monte Carlo simulations, that LTE/LTE-A systems have the potential to accommodate a significantly large number of smart meters within a limited coverage area, with these meters wirelessly transmitting their measurement data in real-time. However, this performance depends on efficient dynamic radio resource management, which in turn would typically rely on an extensive exchange of signaling information. To address this problem, potential techniques for reducing the signaling load between the meters and base stations are proposed and analyzed.

Afterwards, advanced concepts from LTE-A are investigated in conjunction with the proposed algorithms in order to accommodate a larger number of smart meters without disturbing cellular communications. The joint use of carrier aggregation (CA) and relay stations (RSs) to support the IoT traffic emanating from smart meters is investigated. After describing these enhancements, numerical evaluations are presented to determine the number of smart meter devices that can be simultaneously supported with a given bandwidth. Finally, a detailed

[1]This chapter is an extension of the work presented in: E. Yaacoub and A. Kadri, “LTE Radio Resource Management for Real-Time Smart Meter Reading in the Smart Grid”, IEEE ICC 2015 - Workshop on Green Communications and Networks with Energy Harvesting, Smart Grids, and Renewable Energies, London, UK, June 2015.

discussion is presented concerning the number of RSs that should be deployed given a certain density of smart meters, the use of CA, and frequency reuse.

1. Introduction and Background

Current power grids are having a hard time coping with the increasing power consumption and thus are becoming unsustainable. This motivates the ongoing activities and research related to developing a “Smart Grid” (Bannister & Beckett, 2009).

The main purposes of the smart grid are to add intelligence to the grid in order to perform self-coordination, self-awareness, self-healing, and self-reconfiguration, to boost the deployment of renewable energy sources, to augment the efficiency of power generation, transmission, and usage, in addition to shifting and customizing consumers’ energy demands by managing peak loads via demand response (DR) techniques. This necessitates advanced distribution automation and dynamic pricing models relying on automatic meter reading (AMR) and advanced metering infrastructure (AMI) (Lo & Ansari, 2012).

An AMI is one of the main features in smart power grids. It depends on AMR for measuring, collecting, and analyzing energy usage data (Fatemieh et al., 2010), which would represent an essential component of the Big Data era. The deployment of smart meters has several important benefits. For example, it allows real-time information feedback, thus leading to more accurate billing. Furthermore, it allows reducing the peak power demand through the implementation of demand response programs (SUPERGEN, 2012). To perform this interaction with smart meters, a communication media is needed. AMI communications consist mainly of two networks (Purva et al., 2011):

- A home area network (HAN): In this network, power consuming devices inside the home communicate with the power supplier. In most common forms, this takes place via a gateway integrated into the smart power meter. Low power wireless transceivers or in home power line communications (PLC) can be used to carry these communications.
- A neighborhood area network (NAN): This network mainly serves to connect energy meters to data aggregators/collectors. Different means can be used to establish this link. This connection can be performed wirelessly, by a data wired connection to the smart meter, or over the power lines via PLC technology. Once the data reaches the aggregation stations, these can then communicate with the power utility's central servers using leased access lines, wireless microwave links, or PLC.

This chapter presents an AMR/AMI communication approach that can be applied either to directly transmit the data from the smart meters to the utility servers, or to transmit data collected by aggregators to these servers. The proposed approach implements radio resource management (RRM) in an orthogonal frequency division multiple access (OFDMA) system, using the channel state information (CSI) to optimize performance.

An overview of the most relevant works in the literature is presented next, and the differences with the proposed approach are outlined, before proceeding with the rest of the chapter.

In (ON Semiconductor, 2011), PLC is suggested for communications between smart meters and a concentrator that relays the data using GPRS to a central information system. However, PLC faces the challenge of the lack of capacity at higher frequencies (SUPERGEN, 2012). Furthermore, measurements have shown that the characteristics of the PLC channel vary significantly between different countries or regions, due to different wiring practices and loads connected to the system (Bannister & Beckett, 2009). Hence, a solution suitable for one country might not be suitable for another. OFDMA was proposed in (Bannister & Beckett, 2009) to enhance the throughput and reliability of PLC. Although significant enhancements were reached, it was noted in (Bannister & Beckett, 2009) that more sophisticated channel estimation and adaptive feedback techniques are needed in order to further enhance throughput and reliability. Wireless communications could be thought of as the most cost-efficient solution for smart meter deployments, especially when compared to laying additional cables or to using PLC data communications, which would require an upgrade to the power distribution hardware (Purva et al., 2011). Thus, thousands of meters can form a mesh network and communicate using protocols in the public industrial scientific and medical (ISM) frequency bands. The role of the mesh network would be to route the meter data to an aggregator, which in turn relays this data to the power utility, generally using cellular data services such as GPRS (Fatemieh et al., 2010). However, mesh networks face significant challenges related to security and signal privacy. These challenges need to be addressed before promoting the use of mesh networks for AMI (SUPERGEN, 2012).

A two-tier approach was proposed in (Fatemieh et al., 2010) in order to allow the use of TV white spaces for AMI communication: In the first tier, WhiteFi, a system providing connectivity similar to Wi-Fi using the white spaces (Bahl et al., 2009), is used for allowing aggregators to collect the smart meters data. In the second tier, this data is relayed by the aggregators to the utility provider using IEEE 802.22.

One can notice that the majority of the cited previous works above focus on the NAN wireless communication part. This is due to the fact that NAN communications constitute the most challenging part since, within the HAN, devices could communicate with a smart power meter using known short-range communication protocols such as Bluetooth, ZigBee, and WiFi.

In (Le & Le-Ngoc, 2011), a queuing-based resource allocation framework for OFDMA-based wireless networks was proposed. The model can be useful as the last-mile or high speed backhaul part of the power grid communications infrastructure.

In (Khan & Khan, 2012a), WiMAX communications are used to transmit the data of phasor measurement units (PMUs) in the smart grid. The unsolicited grant service (UGS), real-time polling service (rtPS) and best-effort (BE) WiMAX scheduling services are compared and analyzed. PMU measurements are strictly delay-sensitive and they can trigger protection and control systems. The results of (Khan & Khan, 2012a) show that UGS performs best while consuming a significant amount of radio resources. Although periodic frequent AMR readings are important in the smart grid, they can be performed at intervals of few minutes, and are not as critical as critical messages from PMUs that could be due to an alarming situation in the grid.

The performance of a heterogeneous (HetNet) WiFi/WiMAX network was shown to lead to a better delay performance in transmitting the meter readings than a pure WiMAX network in (Khan & Khan, 2012b). In fact, it is expected that this two-tier network, with the presence of WiFi access points closer to the smart meters, and ready to relay the aggregated meter data (using significantly less wireless channels) to the WiMAX network, would lead to better results. However, it should be noted that the proposed approach can be implemented in a HetNet framework, either by implementing the method itself on the two hops (between the meters and aggregator, then between the aggregators and BS), or on the first hop (between the meters and aggregator, then using LTE between the aggregators and BS), or on the last hop (using WiFi between the meters and neighboring aggregators, then using the proposed approach between the aggregators and the BS).

With AMI, most of the traffic is expected to be in the uplink direction. Hence, LTE Time Division Duplex (TDD) was investigated in (Brown & Khan, 2012b) as a possible solution for AMR/AMI using LTE TDD configurations 0, 1, or 6, that are uplink biased. In (Brown & Khan, 2012a), it was compared with LTE Frequency Division Duplex (FDD). Interestingly, although TDD can provide greater flexibility when the split between uplink and downlink data is asymmetrical, FDD leads to better uplink performance in terms of latency. The reasons are mainly due to the delays caused by the alternation of the uplink and downlink slots in LTE TDD. Detailed analysis can be found in (Brown & Khan, 2012a; Brown & Khan, 2012b).

In (Li et al., 2011), it was found that contention based schemes (Aloha) outperform schemes with dedicated channels (TDMA and OFDMA) in terms of delay and packet loss rate. The measurements performed in (Li et al., 2011) led to the conclusion that power consumption changes can be approximated using a Poisson process with small arrival rate, and hence it would be better to send the AMR report only when there is a significant change in the power consumption.

This Chapter investigates the big data challenge imposed by the expected ubiquitous deployment of smart meters along with their real-time transmission of AMR data through machine-to-machine (M2M) communications in the IoT paradigm. AMR/AMI communications in dense deployments of smart meters could have severe impacts on LTE, due to frequent and simultaneous transmission of low data rate information by a very large number of devices. The use of efficient LTE radio resource management (RRM) is studied and analyzed in order to assess if LTE/LTE-A networks can raise this challenge. Thus, this chapter investigates the number of simultaneous smart meter transmissions that can be supported in LTE while using low complexity RRM methods. The investigated approach can be applied either to direct data transmission from the smart meters to the LTE base stations (BSs), or to transmit data collected by aggregators/relay stations (RSs) to the BSs. A high level comparison with the other techniques is presented in Table 1.

Table 1. Comparison of the various AMR/AMI techniques.

Technology	Advantages	Limitations
PLC	Use existing infrastructure, low cost	Location dependent, throughput and reliability problems
Wireless Mesh network	Resiliency and robustness to errors	Privacy of consumers compromised (data of a consumer might go through the device of another)
WiFi	Free spectrum, high data rates	High collisions, Assumes presence of aggregators that will use other techniques for long distamnce transmission (GPRS, LTE, WiMAX, etc.)
LTE	High data rates, long range communications, user privacy protected	High signaling overhead (for relatively frequent but small amounts of data transmitted), possibility of network congestion
Contention-based	Reduces signaling with BS/AP (random access), can be used for long range or short range (as in the Hetnet model)	Possibility of high collisions at very high network loads
Proposed	Same as LTE method, but can be applied to short-range and long-range communications, can be adapted to reduce the signaling overhead, and can use relays and carrier aggregation to increase the number of accommodated meters without disrupting cellular communications	Relatively increased complexity in designing and planning the network

This chapter is organized as follows. After presenting the system model in Section 2, the proposed LTE resource allocation algorithms are presented in Section 3. Simulation results are described and analyzed in Section 4. Practical limitations and implementations are discussed in Section 5. The use of advanced techniques such as carrier aggregation and relays to enhance performance is analyzed in Section 6. Finally, Section 7 presents the conclusions.

2. System Model

The scenario investigated in this chapter consists of smart meters sending real-time measurements to an LTE BS. The system model studied includes two approaches that can be used for AMR in the smart grid. The first approach is depicted in Fig. 1 and consists of smart meters communicating directly with the cellular BS. Although this scenario can be implemented in both urban and rural environments, it is mostly beneficial in rural areas where the sparse habitations and the large distances do not justify the aggregation of data. The second approach is displayed in Fig. 2, and consists of smart meters sending their data to local aggregators. The aggregators collect data from meters in each building or street, and then forward the aggregated data to the LTE BS. ZigBee, WiFi, Bluetooth, PLC, or wired communications can be used on the first short range link between the meters and aggregators. LTE communications can then be used on the second long range link to send the collected data from the aggregators to the BS. The RRM methods and techniques presented in this chapter are applicable to both scenarios. Therefore, the term “devices” is used in the sequel to refer to either smart meters or aggregators communicating with the BS. The term “node” is used to refer to any node in the network, be it a “device” (smart meter or aggregator), or the cellular BS.

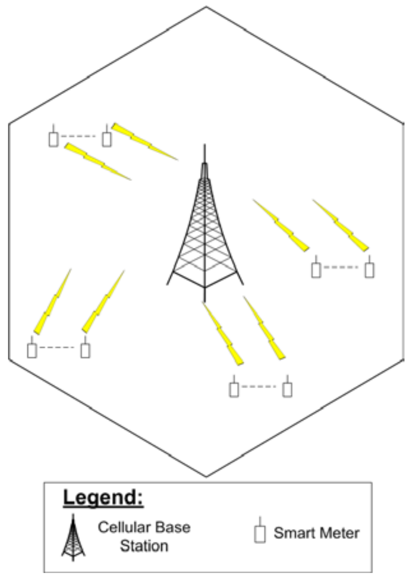

Figure 1. Scenario with direct communications between smart meters and the BS.

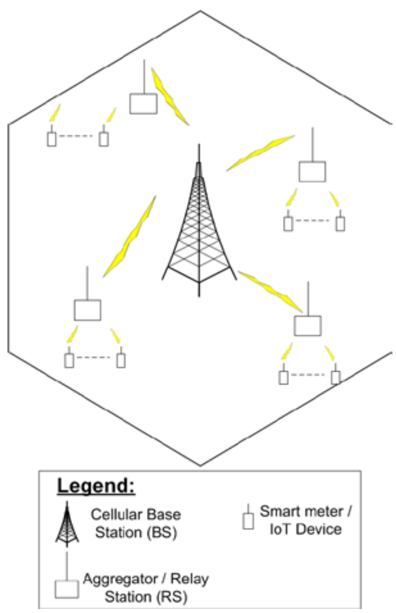

Figure 2. Scenario showing the use of aggregators to relay smart meter data to the LTE BS.

Orthogonal frequency division multiple access (OFDMA) is used as the accessing scheme in LTE downlink (DL). On the other hand, in the LTE uplink (UL), single carrier frequency division multiple access (SCFDMA), which is a modified form of OFDMA, is used (Myung & Goodman, 2008). The LTE spectrum is divided into resource blocks (RBs), such that each RB consists of 12 adjacent subcarriers. The smallest RB allocation time unit is T_{TTI}=1 ms, which is the duration of one transmission time interval (TTI), or, equivalently, the duration of two 0.5 ms slots (3GPP TS 36.211, 2016; 3GPP TS 36.213, 2016). Bandwidth scalability is an important feature of LTE. In fact, a bandwidth of 1.4, 3, 5, 10, 15, and 20 MHz can be used, corresponding, respectively, to 6, 15, 25, 50, 75, and 100 RBs (Myung & Goodman, 2008; 3GPP TS 36.213, 2016). In this chapter, scenarios with 6, 15, 25, or 50 RBs available for resource allocation at the LTE BS are investigated. Actually, this is not the total LTE bandwidth. Instead, this is the bandwidth assumed available for AMR transmissions, out of a total bandwidth of 20 MHz (corresponding to 100RBs). Additional bandwidth can even be available if carrier aggregation is assumed implemented in an LTE-Advanced (LTE-A) setup. This extra bandwidth could be used for other services and/or traditional (i.e. not M2M or AMR) cellular communications. Since in AMI/AMR the most important challenge is to ensure reliable transmissions from the smart meters to the BS, the UL direction is studied in this chapter. Each device is assumed to transmit at a maximum power of 125 mW. This power is equally subdivided among the subcarriers allocated to that device.

2.1 Channel Model

The expression of the channel gain on the wireless link between nodes *k* and *j* over subcarrier *i* can be expressed as:

$$H_{k,j,i,dB} = (-\kappa - \lambda \log_{10} d_{k,j}) - \xi_{k,j,i} + 10\log_{10} F_{k,j,i} \qquad (1)$$

In (1), the first factor corresponds to propagation loss, with κ denoting the pathloss constant, $d_{k,j}$ denoting the distance in km between nodes *k* and *j*, and λ denoting the path loss exponent. The second factor, $\xi_{k,j,i}$, represents log-normal shadowing assumed to have zero-mean and a standard deviation σ_ξ. Finally, the third factor, $F_{k,j,i}$, is used to capture the effect of fast Rayleigh fading with a Rayleigh parameter *a* such that $E[a^2] = 1$, with *E[]* being the expectation operator.

2.2 Data Rate Calculations

Assuming there are *K* devices transmitting to a destination *j* having *N* subcarriers to be allocated, and denoting by $P_{k,j,i}$, $H_{k,j,i}$, and $\sigma^2_{k,j,i}$, the transmit power, channel gain, and total noise power, respectively, of a transmitting device *k*, the signal-to-noise ratio (SNR) between nodes *k* and *j* over subcarrier *i* is expressed as:

$$\gamma_{k,j,i} = \frac{P_{k,j,i} H_{k,j,i}}{\sigma^2_{k,j,i}} \qquad k = 1,\dots,K; \quad i = 1,\dots,N; \tag{2}$$

The peak power constraint of device *k* is given by:

$$\sum_{i=1}^{N} P_{k,j,i} \le P_{k,\max} \qquad k = 1,\dots,K; \tag{3}$$

The inequality in (3) means that the power spent by a device to transmit on all its allocated subcarriers cannot exceed the device’s maximum transmission power $P_{k,\max}$.

The total data rate achieved by node *k* transmitting to node *j* is given by:

$$R_{k,j} = \sum_{i=1}^{N} R^d_{k,j,i}(\gamma_{k,j,i}) \tag{4}$$

In (4), $R^d_{k,j,i}$ corresponds to the discrete data rate that can be achieved on the link between nodes *k* and *j* over subcarrier *i*. Discrete rates represent the quantized bit rates achievable in a practical system, as opposed to continuous rates that can take any non-negative real value according to the Shannon capacity formula $\log_2(1 + \gamma_{k,j,i})$. Discrete rate are expressed as follows:

$$R^{d}_{k,j,i}(\gamma_{k,j,i}) = \begin{cases} r_0, & \eta_0 \le \gamma_{k,j,i} < \eta_1 \\ r_1, & \eta_1 \le \gamma_{k,j,i} < \eta_2 \\ r_2, & \eta_2 \le \gamma_{k,j,i} < \eta_3 \\ \vdots & \\ r_{L-1}, & \eta_{L-1} \le \gamma_{k,j,i} < \eta_L \end{cases} \qquad (5)$$

In (5), η_l is the SNR target needed to achieve the rate r_l with a predefined bit error rate (BER). Note that in the limit, the following equalities hold: $r_0 = 0$, $\eta_0 = 0$, and $\eta_L = \infty$.

In the LTE standard, UL RBs allocated to a single device must be consecutive. Furthermore, the same modulation and coding scheme (MCS) is used and equal power should be allocated for transmission over the subcarriers forming these RBs (3GPP TS 36.213, 2016). Hence, the rate $R_{k,j}$ of a node k communicating with a node j using an MCS with rate r_n bits/symbol over its allocated subcarriers, is given by:

$$R_{k,j} = \frac{r_n \cdot N^{(\mathrm{k,j})}_{\mathrm{RB}} \cdot N^{\mathrm{RB}}_{\mathrm{SC}} \cdot N^{\mathrm{SC}}_{\mathrm{Symb}} \cdot N^{\mathrm{TTI}}_{\mathrm{Slot}}}{T_{\mathrm{TTI}}} \qquad (6)$$

In (6), $N^{(\mathrm{k,j})}_{\mathrm{RB}}$ is the number of RBs allocated by node j to node k, $N^{\mathrm{RB}}_{\mathrm{SC}}$ is the number of subcarriers per RB (equal to 12 in LTE), $N^{\mathrm{SC}}_{\mathrm{Symb}}$ corresponds to the number of symbols per subcarrier during one time slot (equal to six or seven in LTE, depending whether an extended cyclic prefix is used or not), $N^{\mathrm{TTI}}_{\mathrm{Slot}}$ represents the number of time slots per TTI (two 0.5 ms time slots per TTI in LTE), and T_{TTI} is the duration of one TTI (1 ms in LTE) (3GPP TS 36.211, 2016). The adaptive modulation and coding schemes used in LTE are shown in Table 2 (3GPP TS 36.211, 2016; 3GPP TS 36.213, 2016).

Table 2. Discrete rates and SNR thresholds with LTE MCSs

Modulation	Coding Rate	r_l (bits)	η_l (dB)
No Transmission	0	0	-∞
QPSK	78/1024	0.1523	-7.2
QPSK	120/1024	0.2344	-5.8
QPSK	193/1024	0.3770	-3.7
QPSK	308/1024	0.6016	-1.5
QPSK	449/1024	0.8770	0.1
QPSK	602/1024	1.1758	1.8
16-QAM	378/1024	1.4766	4.1
16-QAM	490/1024	1.9141	6.8
16-QAM	616/1024	2.4063	8.9
64-QAM	466/1024	2.7305	10.7
64-QAM	567/1024	3.3223	11.6
64-QAM	666/1024	3.9023	13.9
64-QAM	772/1024	4.5234	16.2
64-QAM	873/1024	5.1152	18.1
64-QAM	948/1024	5.5547	22.4
64-QAM	1 (uncoded)	6.0	26.8

3. LTE Resource Allocation Algorithms

According to the study of (Purva et al., 2011), in order for a smart meter to send real-time readings about energy consumption, it should transmit an amount of information in bits D_{th} during a time period of duration T_{th}, thus achieving a target data rate R_{th}. Therefore, in this section, two LTE RRM algorithms are presented in order to transmit the required number of bits within the specified duration. One algorithm is a simple channel state information (CSI)-unaware algorithm, whereas the other is more advanced since it uses channel state information and is thus a CSI-aware algorithm.

Denoting by $I_{\mathrm{RB},k,j}$ the set of RBs allocated to device k communicating with a device j (could be the BS or an RS), N_{RB} the total number of RBs, and K the number of devices, $U(R_{k,j} \mid I_{\mathrm{RB},k,j})$ is defined as the utility of user k as a function of the data rate $R_{k,j}$ on the link between nodes k and j, given the allocation $I_{\mathrm{RB},k,j}$.

3.1 Channel State Information (CSI) Unaware Resource Allocation Algorithm

Algorithm 1 is a simple CSI-unaware algorithm that systematically allocates one RB per device without considering channel quality in the allocation. Hence, under this approach, each device receives an LTE RB every TTI when the number of devices is less than the number of RBs (Lines 6-15). Otherwise, the devices take turns on the available RBs every TTI, until all the devices are served (Lines 17-29). Algorithm 1 can be considered as a modified version of the well-known round robin (RR) algorithm. The main enhancement is in taking into account a dense deployment of devices ($K > N_{\mathrm{RB}}$) and considering the cumulative performance over T_{th} rather than per TTI scheduling over a duration T_{TTI}.

Algorithm 1 CSI-Unaware RRM Algorithm

1: $N_{\mathrm{TTI}} = \lceil T_{\mathrm{th}} / T_{\mathrm{TTI}} \rceil$
2: $D_{\mathrm{th}} = R_{\mathrm{th}} \cdot T_{\mathrm{th}}$
3: **For all** *k* **do**
4:     $D_{k,j} = 0$
5: **End For**
6: **If** $K \leq N_{\mathrm{RB}}$ **Then**
7:     **For** *t=1* to N_{TTI} **do**
8:         **For** *k=1* to *K* **do**
9:             **For** *n=1* to *K* **do**
10:                 Allocate RB *n* to device *k*: $I_{\mathrm{RB},k,j} = I_{\mathrm{RB},k,j} \cup \{n\}$
11:                 Set $R_{k,j} = R_{k,j,n}$
12:                 $D_{k,j} = D_{k,j} + R_{k,j} \cdot T_{\mathrm{TTI}}$
13:             **End For**
14:         **End For**
15:     **End For**
16: **Else**
17:     **If** $K > N_{\mathrm{RB}}$ **Then**
18:         Divide devices into N_{G} groups: $N_{\mathrm{G}} = \lceil K / N_{\mathrm{RB}} \rceil$
19:         *i=0*
20:         **For** *t=1* to N_{TTI} **do**
21:             **For** *n=1* to N_{RB} **do**
22:                 Allocate RB *n* to device $k = i \cdot N_{\mathrm{RB}} + n$. Hence: $I_{\mathrm{RB},k,j} = I_{\mathrm{RB},k,j} \cup \{n\}$

```
            Set $R_{k,j} = R_{k,j,n}$
            $D_{k,j} = D_{k,j} + R_{k,j} \cdot T_{\text{TTI}}$
        End For
        $i = \text{mod}(i+1, N_{\text{G}})$
    End For
  End If
End If
```

3.2 CSI-Aware Resource Allocation Algorithm

Algorithm 2 is a utility maximization CSI-aware algorithm. Line 1 determines the number of TTIs available to transmit, by each device, the number of data bits D_{th} calculated at Line 2 (where $\lceil \cdot \rceil$ corresponds to the ceiling operation). The method presented at Lines 7-28 is implemented at each TTI. It consists of allocating to device *k* the RB *n* that maximizes the difference $\Lambda_{k,j,n}$ (Line 14), with $\Lambda_{k,j,n}$ representing the marginal utility. This metric corresponds to the gain in the utility function *U* when RB *n* is allocated to device *k* communicating with device *j*, compared to the utility of device *k* before RB *n* was allocated to it. The condition at Lines 19-21 ensures RB continuity in LTE uplink, by forcing the RBs allocated to a given device at a certain TTI to be contiguous. If a device succeeds in transmitting its information before T_{th} has elapsed (e.g. due to high data rates achievable when the channel conditions are favorable), the device is excluded from the resource allocation process (Lines 26-28), in order to allow the devices that did not complete their transmissions to use the remaining resources.

The utility function depends on the data rate, and different functions can be selected depending on the desired quality of service (QoS) requirements. For example, with $U=R_{k,j}$, the algorithm leads to a maximization of the sum-rate of the cell. In this case, devices closer to the BS and/or RS will be favored, whereas other devices will suffer from being in outage. Utility functions providing more fairness can be used to address this problem. When $U=\ln(R_{k,j})$ is used (with ln denoting the natural logarithm), this leads to proportional fair resource allocation (Yaacoub & Dawy, 2012; Song & Li, 2005). Using, in the logarithm, the achievable data rate at the current scheduling instant achieves proportional fairness in frequency (PFF), whereas including the previous scheduling instants by using the cumulative rate (since the start of the data transmission by the device in the current T_{th} time interval), leads to proportional fairness in time and frequency (PFTF) (Yaacoub & Dawy, 2012).

Algorithm 2 CSI-Aware RRM Algorithm

$N_{\text{TTI}} = \lceil T_{\text{th}} / T_{\text{TTI}} \rceil$

$D_{\text{th}} = R_{\text{th}} \cdot T_{\text{th}}$

For all k **do**

  $D_{k,j} = 0$

End For

For $t=1$ to N_{TTI} **do**

  Consider the set of RBs available for scheduling $I_{\text{avail\_RB}} = \{1, 2, \cdots, N_{\text{RB}}\}$

  Consider the set of devices available for scheduling $I_{\text{avail\_dev}} = \{1, 2, \cdots, K\}$

  For all k **do**

    $R_{k,j} = 0$

  End for

  For $n=1$ to N_{RB} **do**

    For All k such that $D_{k,j} < D_{\text{th}}$ **do**

      $\Lambda_{k,j,n} = U\left(R_{k,j} \mid I_{\text{RB},k,j} \cup \{n\}\right) - U\left(R_{k,j} \mid I_{\text{RB},k,j}\right)$

    End for

    Find $k^* = \arg\max_{k; k \in I_{\text{avail\_dev}}} \Lambda_{k,j,n}$

    Allocate RB n to device k^*: $I_{\text{RB},k^*,j} = I_{\text{RB},k^*,j} \cup \{n\}$

    Delete the RB from the set of available RBs: $I_{\text{avail\_RB}} = I_{\text{avail\_RB}} - \{n\}$

    If $\arg\max_k \Lambda_{k,j,n} \neq \arg\max_k \Lambda_{k,j,n-1}$ **then**

      $I_{\text{avail\_dev}} = I_{\text{avail\_dev}} - \{\arg\max_k \Lambda_{k,j,n-1}\}$

    End If

    Calculate the rate of device k^* over RB n: $R_{k^*,j,n}$

    Set $R_{k^*,j} = R_{k^*,j} + R_{k^*,j,n}$

  End For

  $D_{k^*,j} = D_{k^*,j} + R_{k^*,j} \cdot T_{\text{TTI}}$

  If $D_{k^*,j} \geq D_{\text{th}}$ **then**

$$I_{\text{avail\_dev}} = I_{\text{avail\_dev}} - \{k^*\}$$

End If

End For

PFTF is actually equivalent to using U=ln($D_{k,j}$), with $D_{k,j}$ denoting the number of bits transmitted by device k to device j since the start of the current time interval of duration T_{th}. In this chapter, a PFTF utility is used in Algorithm 2, which is a modified version of the algorithm presented in (Yaacoub & Dawy, 2012). It is customized to AMR by considering the overall performance at a time interval of T_{th} rather than T_{TTI}, and by excluding the devices that complete their data transmissions from additional RB allocations within the current T_{th} interval.

4. Simulation Results: Analysis and Comparison of the Results of the two Algorithms

In this section, the simulation results using Algorithms 1 and 2 are presented and analyzed. According to the study of (Purva et al., 2011), to model real-time data transmission by a smart meter, it is assumed that a transaction is performed every two minutes. It consists of accessing the channel for a duration of 430 ms, in order to transmit the meter's data at a rate of 60 kbps. Extending these constraints to an LTE network deployment scenario, a group of devices are considered to be simultaneously scheduled for transmission in an interval T_{th} = 500 ms, consisting of 500 TTIs, with their turn coming periodically every two minutes. The devices that fail to achieve an average target rate R_{th} = 60 kbps within this time period are assumed to be in outage.

4.1 Simulation Results

This section presents the MATLAB simulation results obtained by implementing the methods described in Section 3 under the system model of Section 2. A single LTE cell of radius 500 m is considered, with the BS equipped with an omnidirectional antenna and placed at the cell center. Algorithm 1 is referred to by “RR” and Algorithm 2 by “PFTF”. The fraction of users in outage is displayed in Fig. 3 for both RR and PFTF scheduling, with different numbers of RBs available. PFTF outperforms RR as expected, due to intelligently using CSI in the RRM process. Consequently, more devices are served with PFTF scheduling due to using CSI awareness in the RRM process. However, the price to pay in this case is increased signaling, due to regular CSI feedback to the BS in order to perform CSI-aware scheduling. More details on this problem are discussed and analyzed in Section 5.

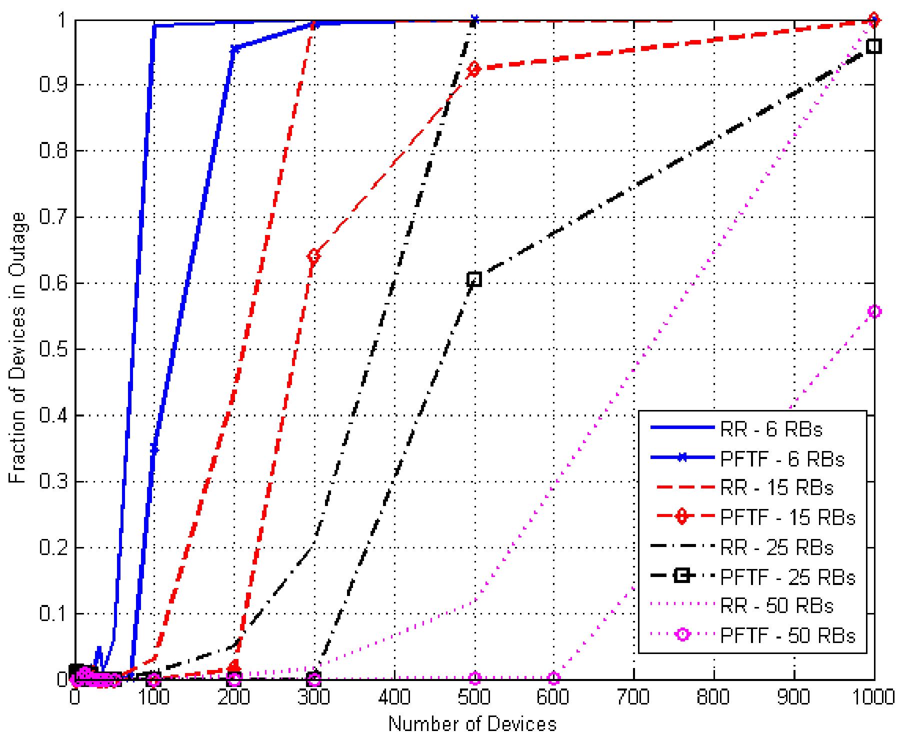

Figure 3. Fraction of Devices in Outage.

In addition, the outage rate is reduced with both methods when the number of RBs increases. Actually, in this case, more resources become available for RRM, thus allowing to serve more devices. Although this is an expected result, it is described in this chapter in order to outline less investigated challenges specific to AMR in the smart grid, or M2M communications in general. Actually, under the IoT paradigm, billions of devices using M2M communications need to coexist with the more “traditional” human-to-human (H2H) cellular traffic, already causing by itself significant load increase on the networks in order to meet the increasing demands. Consequently, the wireless resources should be carefully and judiciously subdivided between H2H and M2M traffic, so that the QoS requirements of both scenarios are successfully met. Table 3 presents the number of smart meters that can be supported for each available bandwidth and RRM method. In other words, Table 3 shows the number of smart meters that can send successfully their data in real-time to the LTE BS with a negligible outage rate. A “negligible” outage rate is considered to be below 0.2% in this chapter.

Table 3. Number of smart meters that can be served successfully for different numbers of available RBs using the two RRM algorithms

	6 RBs	**15 RBs**	**25 RBs**	**50 RBs**
Round Robin (RR)	9500	19000	24000	60000
Proportional Fair (PFTF)	16800	43200	72000	144000

Using the previously described guidelines for real-time transmission of smart meter data, it can be concluded that when K meters are scheduled simultaneously for transmission slots at any given time instant, each BS can accommodate $240K$ smart meters without having any of them in outage. In fact, there are 240 time windows of T_{th} = 500 ms each within a two-minute duration. One of the 240 time windows can be assigned to each smart meter by the BS scheduler in order to transmit periodically the meter readings to the utility company. An example is shown in Fig. 4(a). With K different smart meters accessing the network successfully at each time window (K can be determined from Fig. 3), a total of $240K$ smart meters can be installed per 500 m cell, according to the scenario depicted in Fig. 1. For example, K=500 in the case of PFTF with 50 RBs, and K=50 in the case of PFTF with six RBs, corresponding to 144000 and 16800 meters in the cell, respectively.

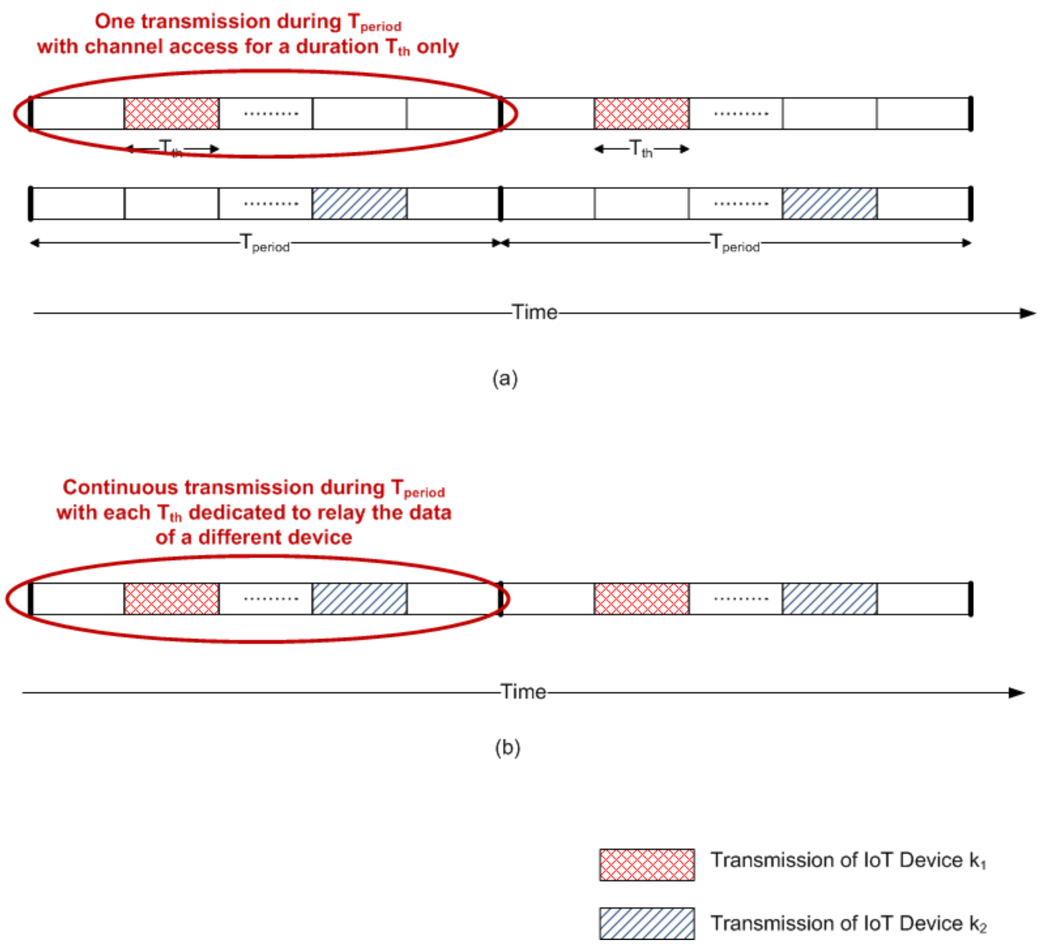

Figure 4. Transmission over slots of T_{th} = 500 ms within two-minute periodic intervals: (a) Direct transmission from smart meters to the BS; (b) Transmission by the aggregator to the BS after receiving the data from the smart meters.

In the scenario of Fig. 2, smart meters send their data to an aggregator first, using PLC, a wired connection, or a short range wireless transmission on the ISM band. Afterwards, a number K of aggregators can be determined from Fig. 3. These K aggregators can simultaneously transmit to the BS the data that they have previously aggregated, without having any of them in outage. In this scenario, the same number of meters ($240K$) can still be accommodated. In fact, each aggregator can collect the data of 240 smart meters, by receiving the data from each meter in a separate 500 ms time window (in a sort of TDMA fashion for a total duration of two minutes). Then, it can relay this data to the BS over the LTE network without interruption over the two minute periodic interval, as shown in the example of Fig. 4(b). Thus, instead of having K smart meters scheduled to transmit simultaneously in time windows of 500 ms, there will be K aggregators, each sending the data of 240 meters, and transmitting continuously at a rate of 60 kbps. Additional details on using relays and carrier aggregation are discussed in Section 6.

5. Analysis of Signaling and Feedback Load for AMR in LTE

In the LTE standard, whenever a device has data to transmit, it sends a scheduling request to the BS. The BS responds by sending to the device an initial uplink grant (3GPP TS 36.331, 2014). After transmitting on the allocated resources, if the device still has data to transmit, it sends to the BS a buffer status report containing the amount of remaining data. The BS then sends subsequent uplink grants as appropriate in order to allow the device to transmit all its data (3GPP TS 36.321, 2014). The delays incurred during this process are analyzed in detail in (Brown & Khan, 2012a).

In this section, some ideas that can reduce the overhead of RRM in LTE uplink in the specific case of AMR/AMI are discussed. In the AMR/AMI scenario, devices are fixed and hence the channel is not expected to change too fast. Consequently, the frequency of CSI feedback or estimation can be reduced. Scheduling is performed at the scale of 1 ms in order to give turns for all devices to transmit, not because the channel conditions change at this speed. CSI estimation on uplink frequencies can be done at a much slower timescale, e.g. hundreds of milliseconds. In addition, since the transmissions are periodic and the amount of data at each transmission is known, the BS can assign the scheduling grant for that device in advance without having to wait for the device to ask for a grant. The device can then transmit periodically using this grant in its specified time. The BS can always change the grant, e.g. after CSI feedback/estimation, or to make sure the device is synchronized to the time interval allotted to it by the BS. This process can be done periodically at fixed (relatively long) time intervals, at a much slower time scale than the current procedure in the standard. Moreover, whenever meter data is not received, or received in error, there is no need for frequent retransmissions, except when critical information is being sent by the meter. Retransmissions can be reduced or canceled in the case of “routine” readings. For example, if the role of AMR is to perform simple readings in real-time, then in case of outage due to packet losses, the updated information can be transmitted at the next transmission period, e.g., after two minutes in the approach of (Purva et al., 2011) adopted in the simulation model of this chapter. These enhancements are in-line with planned enhancement in LTE release 14 (LTE-Advanced Pro) in terms of latency reduction, especially for small data packets, and enhancements for machine type communications (standard term referring to M2M) (Astely et al., 2016).

6. Using LTE-A Concepts to Accommodate Large Numbers of Smart Meters

OFDMA-based relays are part of the state-of-the-art and next generation LTE-based wireless communications systems (Akyildiz et al., 2010; Osseiran et al., 2011). RRM in the presence of relays faces an additional challenge, since resource allocation should be performed on the links between the BS and RS, in addition to the links between the BS/RS and the mobile users (Salem et al., 2010) or M2M devices. Carrier Aggregation (CA) is an added enhancement in the LTE-Advanced (LTE-A) system that could help address this challenge, by allowing multiple carriers or bands to be aggregated together. Users can thus be scheduled on continuous or non-continuous component carriers (Ratasuk et al., 2010). Another enhancement is the use of re-farmed GSM carriers for IoT/M2M transmissions (Astely et al., 2016). Actually, since a single RB is being allocated for each device at a given TTI, this RB could consist of a re-farmed GSM channel in an “unused” GSM spectrum (or actually used for LTE transmissions). The 200 kHz bandwidth of a GSM channel coincides perfectly with that of an LTE RB (12 subcarriers of 15kHz each, in addition to guard bands). This feature is denoted by “narrowband IoT” in Release 13 of the standard and is expected to be refined in Release 14 (Astely et al., 2016). Thus, the proposed methods can be implemented with classic CA or by using OFDMA transmission over a re-farmed GSM spectrum.

Hence, this section studies the joint use of CA and RSs in OFDMA-based 5G networks to address the problem of M2M communications with a large number of devices using IoT.
In fact, the problems of dimensioning and planning cellular networks should be addressed in order to cope with the increased number of connected devices. Using the RRM techniques described in the previous sections on the long range (LR) BS-RS and the short range (SR) RS-device links, the frequency and network planning process would consist of determining the number of relays to be deployed, their positions, and the resources allocated to each relay, such

that the network can simultaneously satisfy the QoS requirements of both the M2M and the traditional human-to-human (H2H) traffic.

Hence, LTE bandwidth can be allocated to IoT traffic in three ways:

- Using bandwidth scalability in LTE, a fraction of the total 20 MHz bandwidth can be made available for SR transmissions from devices to RSs, another orthogonal fraction can be used for LR RS-BS transmissions, while a third fraction can be used for H2H traffic.
- Using CA, up to 100 MHz, corresponding to 500 RBs, can be used, if available, to provide resources for LR and SR M2M links, in addition to the H2H links.
- Re-farmed GSM spectrum (with 200kHz allocations) could also be aggregated with LTE bandwidth for the purpose of IoT transmissions (Astely et al., 2016).

Section 6.1 presents some network planning and dimensioning guidelines, whereas Section 6.2 presents numerical examples.

6.1 RS and Resource Planning for IoT Traffic

The following notation is used:

- $N_{\text{Sim-D}}^{\text{RB}}$: Number of devices that can be scheduled simultaneously over a single RB using RRM with PFTF scheduling.
- $N_{\text{Cons-D}}^{\text{TDMA}} = T_{\text{period}} / T_{\text{th}}$: Number of T_{th} time slots or windows within a transmission period T_{period}.

The BS scheduler allocates one of the $N_{\text{Cons-D}}^{\text{TDMA}}$ time windows to each device for periodically transmitting its readings, as shown in Fig. 4(a). Consequently, the number $N_{\text{Sim-D}}^{\text{RB}} \cdot N_{\text{Cons-D}}^{\text{TDMA}}$ of devices can be served by a single RB in a given LTE cell, due to the possibility of allowing $N_{\text{Sim-D}}^{\text{RB}}$ different devices to access the network at each time window.

Similarly, in a scenario with RS deployment, a number $N_{\text{Sim-D}}^{\text{RB}}$ of RSs can successfully relay their aggregated data to the BS without being in outage. In such a scenario, the same number of IoT/M2M devices $N_{\text{Sim-D}}^{\text{RB}} \cdot N_{\text{Cons-D}}^{\text{TDMA}}$ can be served. In fact, each RS can collect the data of $N_{\text{Cons-D}}^{\text{TDMA}}$ devices, by receiving the data of each device in a separate T_{th} time window, in a sort of TDMA fashion for a total duration T_{period}. Afterwards, the RS sends the received data to the BS over the LTE network over the whole T_{period} interval without interruption, as shown in the example of Fig. 4(b). Thus, instead of scheduling $N_{\text{Sim-D}}^{\text{RB}}$ devices to transmit simultaneously in time windows of duration T_{th}, a number $N_{\text{Sim-D}}^{\text{RB}}$ of RSs will be scheduled, with each RS transmitting continuously the aggregated data of $N_{\text{Cons-D}}^{\text{TDMA}}$ devices at a rate of R_{th} kbps. In this scenario, orthogonal LR and SR RBs would be used due to simultaneous LR and SR transmissions. In addition, the RSs would be operating in duplex mode.

A broad range of practical intermediate scenarios can occur between the two extreme scenarios shown in Fig. 4, thus corresponding to different combinations of RSs and IoT devices connected to each RS. Let $N_{\text{RB,LR}}$ be the number of RBs allocated by the BS for LR communications between the BS and RSs, and $N_{\text{RB,RS}}$ the number of RBs available per relay for allocation on SR links. As mentioned previously, these RBs should be orthogonal. Furthermore, the required number of RSs can be determined by the density of M2M devices in different hotspots of a given cell. Consequently, the network planning process will involve a tradeoff between the number of RSs, the availability of orthogonal RBs (with or without CA, with or without re-farmed GSM spectrum, etc.), and the frequency reuse factor over the SR relay-controlled areas within the same cell. These tradeoffs are clarified by the following analysis.

Let *x* and *y* be two variables that satisfy the following:

$$x \cdot y = N_{\text{Sim-D}}^{\text{RB}} \cdot N_{\text{Cons-D}}^{\text{TDMA}} \tag{7}$$

The number of RSs that are required for supporting the IoT/M2M traffic in the considered area is expressed as:

$$N_{\text{RS}} = x \cdot \frac{N_{\text{RB,LR}}}{N_{\text{RB,RS}}} \tag{8}$$

The number of IoT/M2M devices that are sending data to a single relay is expressed as:

$$N_{\text{D,RS}} = y \cdot N_{\text{RB,RS}} \tag{9}$$

Section 6.2 presents some numerical results obtained by using equations (7)-(9).

6.2 Simulation Results for Various RS and CA Scenarios

Revisiting the results of Section 4.1, and considering only those of the CSI-aware Algoritm 2 (using PFTF scheduling), the number of nodes that can be successfully served by a single BS for a given available bandwidth is shown in Table 4. By “successfully served”, it is meant that the percentage of nodes in outage does not exceed 0.2%. This represents the number of nodes that can send successfully their data in real-time to the LTE BS while keeping the outage rate negligible. In this case, the term “node” can refer either to an RS or an M2M device (sensor, smart meter, etc.) transmitting its data directly to the BS. To obtain the results shown in Table 4, Algorithm 2 was simulated with a single BS while increasing the number of devices, until the percentage of devices in outage reached 0.2%.

From Table 4, guidelines can be reached for planning an LTE network with relay deployment in order to serve IoT/M2M traffic. In this chapter, the network is planned by using the results of Table 4 after considering a reduction by a safety margin of 15% and then rounding off the numbers. The purpose of this approach is to make sure that the network is not under-dimensioned in terms of the number of needed RSs. Interestingly, it can be seen that using Algorithm 2, almost a fixed number of devices can be served simultaneously over a single RB. By “simultaneously” it is not assumed that the nodes use the RB at the same TTI (which would certainly lead to collisions and interference), but rather that they are simultaneously scheduled to transmit over the same interval T_{th} = 500 ms, that consists of 500 LTE TTIs. Through intelligent RRM using PFTF scheduling, each of the nodes receives a subset of these 500 TTIs to transmit its data, with only one node transmitting at a given TTI over a given subcarrier. Then they wait for T_{period} = 120 s in order to be scheduled on another T_{th} slot. Hence, the results of the PFTF algorithm in Table 3 correspond to those of the first row in Table 4, multiplied by $N_{\text{Cons-D}}^{\text{TDMA}} = 240$. These results correspond to the LR links. The approach presented in section 6.1 allows using these simulation results for dimensioning the cellular network depending on the expected locations of the IoT devices, and for determining the required number of relays in order to cover the hotspot areas.

Table 4. Number of smart meters that can be served successfully and simultaneously for different numbers of available RBs using Algorithm 2

	6 RBs	**15 RBs**	**25 RBs**	**50 RBs**
Number of served nodes	70	180	300	600
Number of served nodes after 15% reduction	60	150	250	500
Number of nodes served by RB	10	10	10	10

Different configuration examples are shown in Table 5. For example, the first case in Table 5 (500 relays each serving 240 devices) corresponds to a relatively sparse deployment compared to the second case (50 relays each serving 2400 devices), which represents a scenario with dense hotspots of M2M devices. Consequently, a mobile operator can plan his network according to the expected deployment of M2M devices. The operator would determine the number of needed RSs and then allocate a suitable number of RBs for each. For example, the deployment of smart meters in a dense residential area has different network planning requirements than the deployment of environment monitoring sensors in a rural area.

In the scenario of 50 RSs each serving 2400 devices, a possible solution is to have 50 orthogonal RBs, corresponding to a bandwidth of 10 MHz, dedicated for SR links, with each RS scheduling the devices over one RB. Another orthogonal set of 50 RBs would be dedicated for LR links between RSs and the BS. The total bandwidth would be 20 MHz, or 100 RBs, dedicated to M2M communications. With carrier aggregation, H2H traffic can be accommodated over another 20 MHz. This allows the separation the service of the two traffic categories and hence maintaining their QoS separately. This corresponds to serving 120000 M2M devices in a single cell of radius 500 m. If, for example, 500 relays are used, with each relay using one of the 50 orthogonal RBs, then frequency reuse should be implemented in order to minimize interference. In that case, orthogonal RBs can be allocated for groups of 50 RSs, and then reused over other groups, and so on.

Table 5. Examples of capacity planning of the network using different configurations with $N_{\text{Sim-D}}^{\text{RB}} = 10$ and $N_{\text{Cons-D}}^{\text{TDMA}} = 240$

Configuration example	**Configuration example with $N_{\text{RB,LR}}$ = 50 and $N_{\text{RB,RS}}$ = 1**
$N_{\text{RS}} = 10N_{\text{RB,LR}}/N_{\text{RB,RS}}$ relays each serving $N_{\text{D,RS}} = 240N_{\text{RB,RS}}$ devices	N_{RS} = 500 relays each serving $N_{\text{D,RS}}$ = 240 devices
$N_{\text{RS}} = N_{\text{RB,LR}}/N_{\text{RB,RS}}$ relays each serving $N_{\text{D,RS}} = 2400N_{\text{RB,RS}}$ devices	N_{RS} = 50 relays each serving $N_{\text{D,RS}}$ = 2400 devices
$N_{\text{RS}} = 2N_{\text{RB,LR}}/N_{\text{RB,RS}}$ relays each serving $N_{\text{D,RS}} = 1200N_{\text{RB,RS}}$ devices	N_{RS} = 100 relays each serving $N_{\text{D,RS}}$ = 1200 devices
$N_{\text{RS}} = 5N_{\text{RB,LR}}/N_{\text{RB,RS}}$ relays each serving $N_{\text{D,RS}} = 480N_{\text{RB,RS}}$ devices	N_{RS} = 250 relays each serving $N_{\text{D,RS}}$ = 480 devices

The simulation results of Tables 3-5 are obtained by assuming that devices transmit a their maximum power of 125 mW in the LR. However, in practice, RSs would be placed at much shorter distances from the devices, thus allowing significantly less power to be used for SR transmissions to the RSs. With a reuse factor as large as 50, this leads to a significant interference reduction while at the same time preserving the power of M2M devices (Astely et al., 2016).

7. Conclusions

This chapter investigated the scheduling load added on a long term evolution (LTE) and/or LTE-Advanced (LTE-A) network when automatic meter reading (AMR) in advanced metering infrastructures (AMI) is performed using internet of things (IoT) deployments of smart meters in the smart grid.

Radio resource management algorithms were proposed in order to perform dynamic scheduling of the meter transmissions, and the simulation results showed that LTE can accommodate a significantly large number of smart meters with real-time readings in a limited coverage area.

Methods for reducing the signaling load between the meters and base stations were discussed to allow the practical implementation of the proposed methods.

Furthermore, advanced concepts from LTE-A, such as carrier aggregation and relay stations, were investigated in conjunction with the proposed algorithms in order to support the IoT traffic emanating from a larger number smart meters. Finally, a detailed analysis was presented in order to plan an AMI/AMR network by determining the number of RSs required depending on the density of smart meters, the use of carrier aggregation, and frequency reuse.

It should be noted that current and future LTE standardization releases are moving in the direction presented in this work, namely the support of massive machine type communications (mMTC), MTC being the 3GPP standard term for M2M, in Releases 13 and 14, as mentioned in (Astely et al., 2016) and discussed in this chapter (e.g. in Section 6). Specifically, the concept of Narrowband IoT is being investigated as a potential solution to frequent low data rate communications from IoT devices, as in smart meter applications. LTE-A mMTC applications span a breadth of industry sectors, including medical and mHealth, building automation, environment monitoring, industrial processes, and vehicular networks, in addition to energy and smart metering/smart grids investigated in this chapter. Products supporting the new standards will gradually emerge in the market, and power retailers are expected to incorporate the new enhancements in future smart meters. Deployments of these smart meters would be performed more efficiently if a collaboration agreement is made between power retailers and the mobile network operators, in order to make sure the cellular networks are adequately planned and dimensioned to support the expected smart meter traffic. Furthermore, such an agreement should cover pricing and billing aspects, since frequent periodic data transmissions over the network should not entail excessive billing, neither for the end-user (having the smart meter installed in his/her apartment for example), nor on the power retailer (responsible for deploying, managing, and maintaining the smart meters). Another aspect that should be taken into consideration is standardization in smart grids, and the presence of various communication systems that can contribute to smart grid deployments. In fact, the National Institute of Standards and Technology (NIST) Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0, named over 20 IEEE standards among many other IEEE standards that are related to smart grid development, and identified aspects where additional standardization efforts are required. Interoperability between these smart grid standards with the 3GPP standards governing cellular networks should be put in place in order to take full advantage of smart grids and future cellular networks, by carefully planning the HAN/NAN parts of the network and the most suitable technologies used in each part, thus leading to a fruitful synergy between LTE-A and smart grids.

References

3rd Generation Partnership Project (3GPP), (2016). 3GPP TS 36.211 3GPP TSG RAN Evolved Universal Terrestrial Radio Access (E-UTRA) Physical Channels and Modulation, version 13.1.0, Release 13.

3rd Generation Partnership Project (3GPP), (2016). 3GPP TS 36.213 3GPP TSG RAN Evolved Universal Terrestrial Radio Access (E-UTRA) Physical layer procedures, version 13.1.1, Release 13.

3rd Generation Partnership Project (3GPP), (2014). 3GPP TS 36.321 LTE Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) Protocol Specification, version 12.2.0, Release 12.

3rd Generation Partnership Project (3GPP), (2014). 3GPP TS 36.331 LTE Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol Specification, version 12.2.0, Release 12.

Akyildiz, I., Gutierrez-Estevez, D., and Reyes, E. (2010). The Evolution to 4G Cellular Systems: LTE-Advanced. *Physical Communication*, 3(4), 217–244.

Astely, D., Stattin, M., Wikstrom, G., Cheng, J.-F., Hoglund, A., Frenne, M., Blasco, R., Huschke, J., and Gunnarsson, F. (2016). LTE Release 14 Outlook. *IEEE Communications Magazine*, 54(6), 44-49.

Bahl, P., Chandra, R., Moscibroda, T., Murty, R., and Welsh, M. (2009). White Space Networking with Wi-Fi Like Connectivity. *SIGCOMM Comput. Commun. Rev.*, 39(4), 27-38.

Bannister, S. and Beckett, P. (2009). Enhancing powerline communications in the "Smart Grid" using OFDMA. *Australasian Universities Power Engineering Conference (AUPEC),* 1-5, Adelaide, Australia.

Brown, J., and Khan, J. Y. (2012). Performance comparison of LTE FDD and TDD based Smart Grid communications networks for uplink biased traffic. *IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 276-281, Tainan, Taiwan.

Brown, J., and Khan, J. Y. (2012). Performance analysis of an LTE TDD based smart grid communications network for uplink biased traffic. *IEEE Globecom Workshops*, 1502-1507, Anaheim, California, USA.

Fatemieh, O., Chandra, R., and Gunter, C. A. (2010). Low Cost and Secure Smart Meter Communications using the TV White Spaces. *3rd International Symposium on Resilient Control Systems (ISRCS)*, 37 - 42, Idaho Falls, ID, USA.

Khan, R.H., and Khan, J. Y. (2012). Wide area PMU communication over a WiMAX network in the smart grid. *IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 187-192, Tainan, Taiwan.

Khan, R.H., and Khan, J. Y. (2012). A heterogeneous WiMAX-WLAN network for AMI communications in the smart grid. *IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 710-715, Tainan, Taiwan.

Le, L.B., and Le-Ngoc, T. (2011). QoS provisioning for OFDMA-based wireless network infrastructure in smart grids. *24th Canadian Conference on Electrical and Computer Engineering (CCECE)*, 813-816, Niagara Falls, Ontario, Canada.

Li, H., Han, Z., Lai, L., Qiu, R.C., and Yang, D. (2011). Efficient and reliable multiple access for advanced metering in future smart grid. *IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 440-444, Brussels, Belgium.

Lo, C.-H., and Ansari, N. (2012). The Progressive Smart Grid System from Both Power and Communications Aspects. *IEEE Communications Surveys & Tutorials*, 14(3), 799-821.

Myung, H. G., and Goodman, D. J. (2008). *Single Carrier FDMA: A New Air Interface for Long Term Evolution*. John Wiley and Sons, Chichester, UK.

ON Semiconductor. (2011). Speeding up the Smart Grid: Technique for Delivering More Robust, Higher Data Rate Communications for Automatic Meter Reading. Tech. Report TND6018/D.

Osseiran, A., Monserrat, J., and Mohr, W. (2011). *Mobile and Wireless Communications for IMT-Advanced and Beyond*. John Wiley and Sons, Chichester, UK.

Purva, A., Bumanlag, J., Edelman, B., and Doetsch, U. (2011). “Spectrum Needs for Wireless Smart Meter Communications. *Tech. Report*, University of Colorado, Boulder.

Ratasuk, R., Tolli, D., and Ghosh, A. (2010). Carrier Aggregation in LTE-Advanced. *In Proc. IEEE VTC Spring 2010*, pp. 1–5.

Salem, M., Adinoyi, A., Rahman, M., Yanikomeroglu, H., Falconer, D., Kim, Y.-D., Kim, E., and Cheong, Y.-C. (2010). An Overview of Radio Resource Management in Relay-Enhanced OFDMA-Based Networks. *IEEE Communications Surveys and Tutorials*, 12(3), 422–438.

Song, G., and Li, Y. (2005). Cross-Layer Optimization for OFDM Wireless Networks-Part I: Theoretical Framework. *IEEE Transactions on Wireless Communications*, 4(2), 614-624.

SUPERGEN:HiDEF (Highly Distributed Energy Futures). (2012). Smart Meters for Smart Grids. Briefing Paper.

E. Yaacoub, E., and Dawy, Z. (2012). *Resource Allocation in Uplink OFDMA Wireless Systems: Optimal Solutions and Practical Implementations*. JohnWiley and Sons / IEEE press, NY, ISBN: 978-1-1180-7450-3.