D6.1.3: Advanced Smart Grid Communication Concept

Revision History

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Abstract

This report contains the distribution system input scenario and the results from the corresponding LTE network dimensioning studies.

The scenario is based on selected use cases of the Vattenfall / Finland distribution system network which require wireless communications.

Two LTE deployment scenarios are considered:

- a typical CSP provided LTE MBB network as well as
- a dedicated LTE network for the utility which is optimized for coverage.

Average and peak load capacity utilization of the LTE core and radio network are analyzed in detail for the selected use cases.

Additionally, the feasibility of using LTE for satellite access is investigated.

Table of Contents

1 Preface

This report was done as a part of the Finnish national research project "Smart Grid and Energy Market" SGEM.

It was funded by Tekes – the Finnish Funding Agency for Technology and Innovation and the project partners.

NSN would like to thank the partners Vattenfall, Emtele, Violasystems and TeliaSonera for providing background information and the good cooperation.

Chapter 4.7 on satellite access was contributed by Elektrobit, the remaining chapters were contributed by NSN.

2 Scope

This report contains the distribution system input scenario and the results from the corresponding LTE network dimensioning studies.

The scenario is based on selected use cases of the Vattenfall / Finland distribution system network which require wireless communications.

Updates and corrections to the scenario data reported earlier in the SGEM deliverable D6.1.1: “Consolidated communication requirement descriptions” [18] are included in this report. For the convenience of the reader, the revised assumptions (and related text / tables) of the SGEM deliverable D6.1.1 is integrated into this present report.

Two LTE deployment scenarios are considered:

- a typical CSP provided LTE MBB network as well as
- a dedicated LTE network for the utility which is optimized for coverage.

Average and peak load capacity utilization of the LTE core and radio network are analyzed in detail for the selected use cases.

Additionally, the feasibility of using LTE for satellite access is investigated in chapter 4.7.

3 Introduction, Motivation and Methodology

Within the 2nd FP of SGEM detailed LTE radio and core network dimensioning studies have been carried out by Nokia Siemens Networks. The distribution system input scenario and corresponding study results are documented in this report. Updates and corrections to the scenario data reported earlier in the SGEM deliverable D6.1.1: “Consolidated communication requirement descriptions” [18] are also included in this report.

Dimensioning studies gauge the amount and impact of SG communications traffic and allow comparisons to mobile broadband traffic carried in LTE networks. They also provide a better understanding of the specific characteristics of the SG M2M traffic and the resulting requirements on the underlying radio communication system. The LTE network dimensioning studies are also basis for possible further economic studies in SGEM FP3 such as CAPEX / OPEX comparisons for various LTE deployment scenarios and configurations.

For utility communications it is necessary to consider in addition to the average SG data traffic volumes also the peak loads during larger scale power outages and faults (e.g. due to many simultaneous alarms of meters / RTUs). Any limitations in the communication system due to congestion would impact the useful functionality which could be implemented into DMS.

SG related communications requirements are very use case specific. In addition to the schedule of meter reads, the modeling of use cases related to power outage and fault scenarios which may result in high or peak session densities (signaling transactions) requires detailed input assumptions. These cannot be easily found in the open literature. While the use case volumetric data collected by NIST [4,5] covers a broad range of future SG use cases, the detail of this data is considered as not sufficient to study the relevant distribution automation use cases in Finland in depth.

In order to make the LTE network dimensioning studies concrete, a case study approach is therefore utilized. As the Vattenfall / Finland distribution system possess already today a high degree of automation and also makes extensive use of wireless communications (based on GPRS), it is an ideal starting point for defining meaningful power and communications system scenario data.

In a first version of this report this will be done for today’s use cases such as AMR, use of AMR alarms in DMS for MV/LV outage management and MV feeder automation. This will establish a baseline scenario which can be verified against empirical data obtained from current communication arrangements. In a revised version of this report during FP3 more speculative SG use cases will be added which could materialize around 2020 such as more advanced distribution automation concepts, retrieving disturbance files from primary substations, video surveillance, etc.

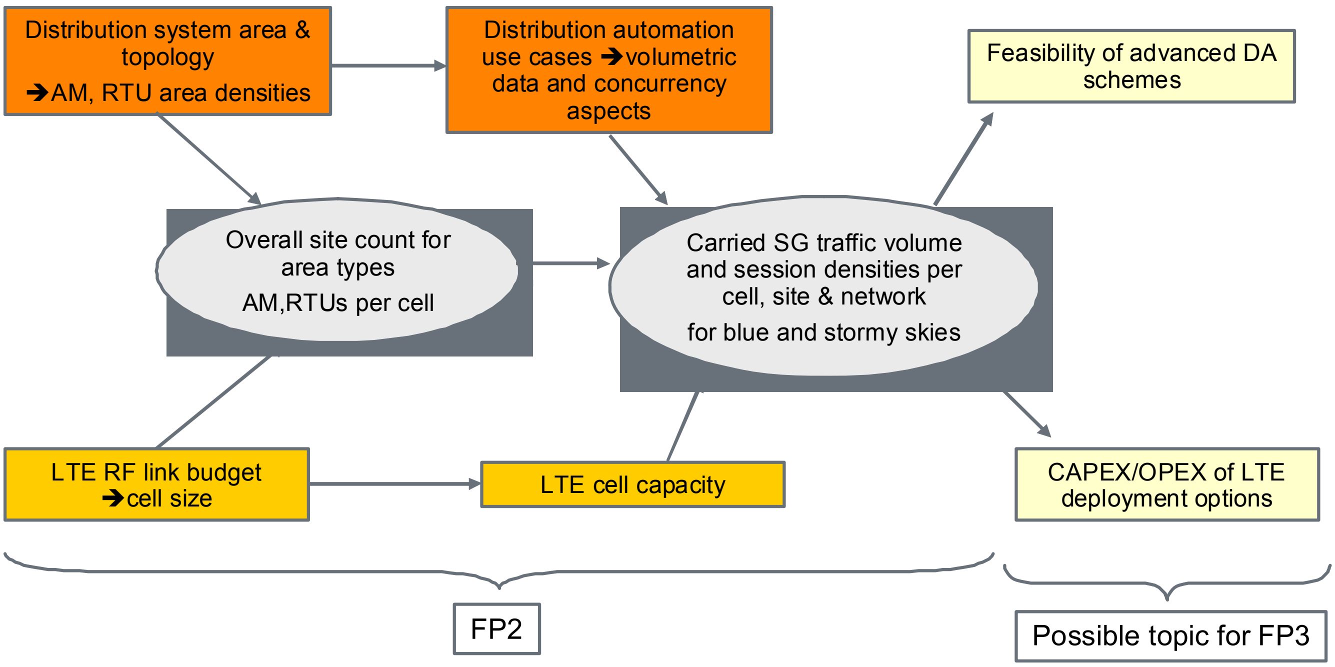
The related communications traffic with the field devices (automatic meters, RTUs) is assumed to be carried exclusively wirelessly and furthermore, is assumed to be aggregated into a single LTE network.

Two LTE deployment scenarios are considered:

- a typical CSP provided LTE MBB network as well as
- a dedicated LTE network for the utility which is optimized for coverage.

Fig. 3-1. shows the proposed methodology for the LTE network dimensioning case study. Previous work for GPRS along similar lines can be found in [13].

Fig. 3-1. Proposed methodology of the LTE network dimensioning case study



Scenario parameters related to the orange and yellow colored boxes are as follows:

Distribution system area & topology:

- % distribution of area types (urban, rural,…)
- average amount of MV, LV feeders, transformers and customers per area type
- average length of feeders
- AM, RTU densities per area type

Distribution automation use cases volumetric data and concurrency aspects:

- selection of relevant use cases and their underlying communication events
- communication transactions and data volumes related to the events
- protocol overheads (TCP/IP, VPN, heartbeat,...)
- event frequencies (e.g. fault+alarm frequencies, meter reads)
- concurrency aspects of events (e.g. how many meters are read per hour, how many alarms occur per hour during storms)
- how meter traffic (reads, alarms) are concentrated / configured behind concentrating modems

LTE Radio link budget (RLB), cell size:

- AM, RTU related RF site parameters needed for RLB
- LTE spectral efficiency figures and resulting per cell and aggregate RAN air interface capacity for the 2 deployment cases

Output parameters related to the gray colored boxes are as follows:

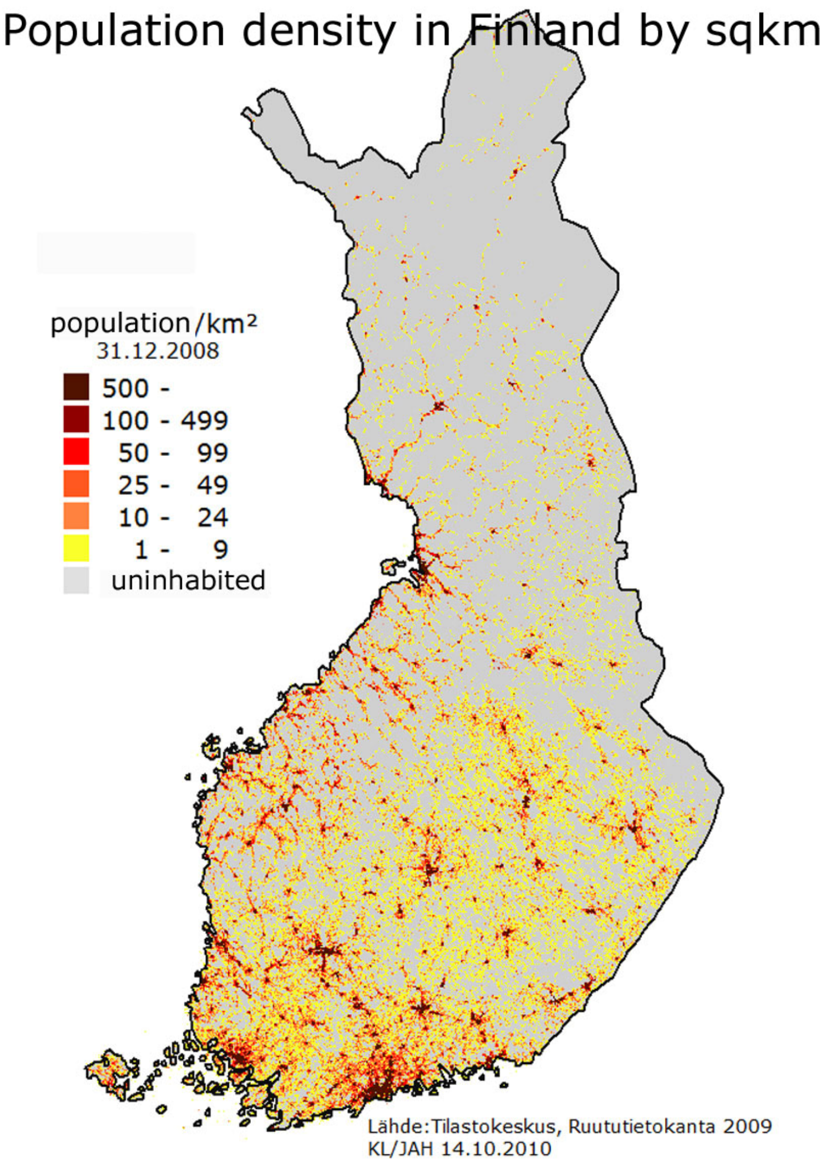
- # of sites needed for coverage of the utility service area
- aggregate traffic volumes on per-cell and core network (EPC) basis
- analysis of different timescales: monthly, busy hour, peak load seconds
- Average and peak load capacity utilization of the LTE core and radio network

These data are captured in suitable EXCEL files to facilitate further analysis in subsequent deliverables. A core part of this is a flexible database for SG traffic events describing their detailed characteristics which is utilized by the various traffic analysis sheets. This SG traffic event database can be readily extended for additional uses cases in future studies.

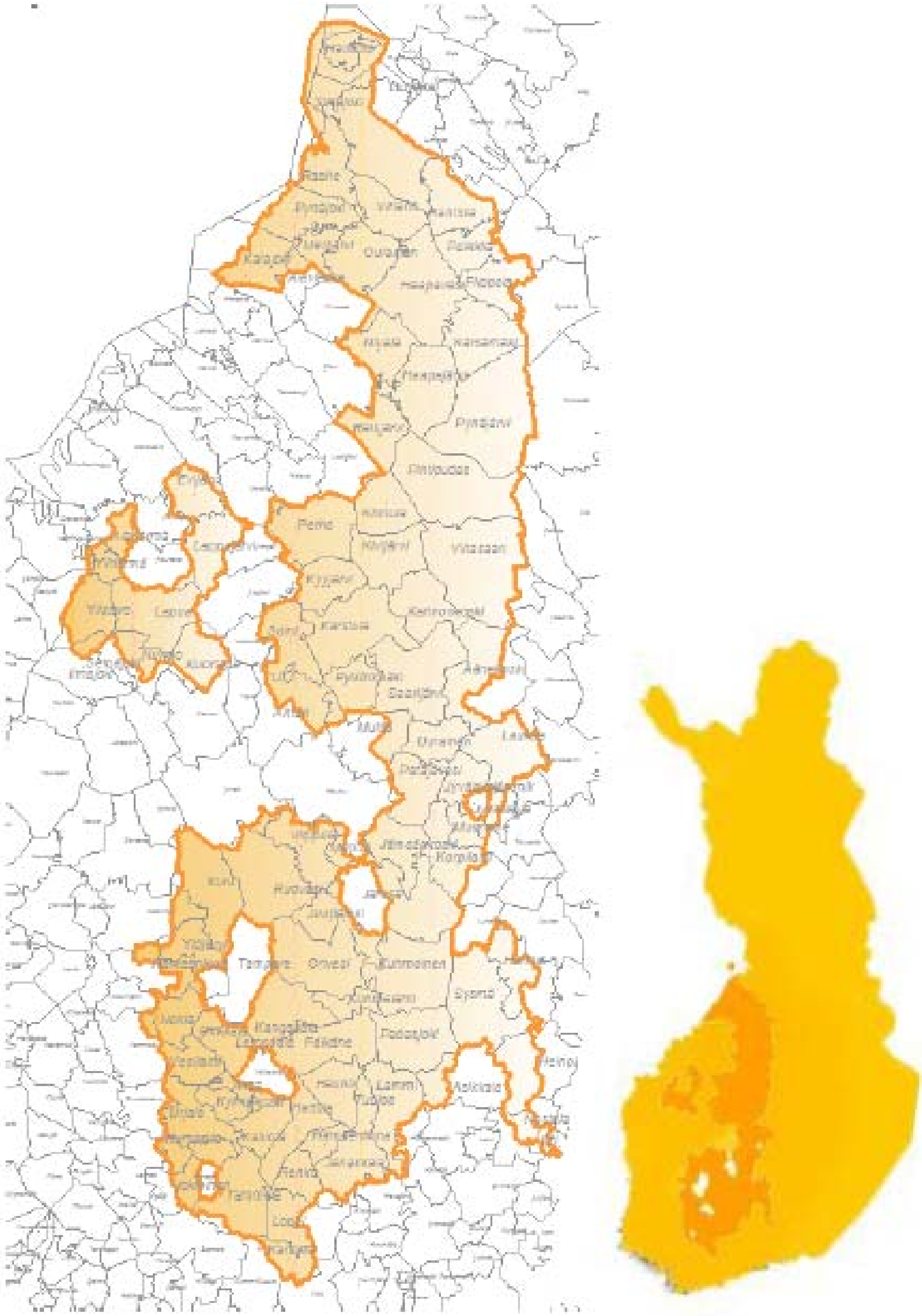
4 Scenario for communication requirements

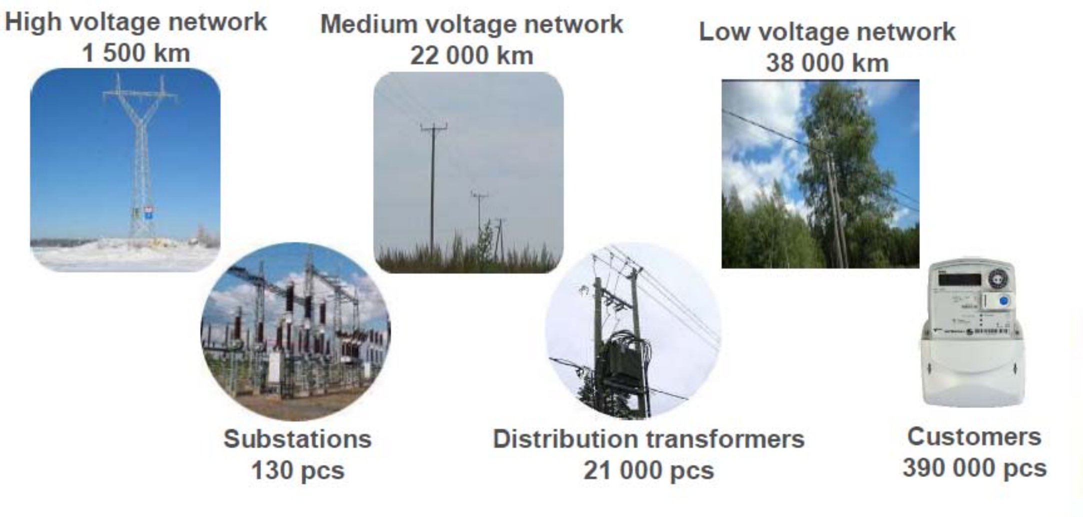
4.1 Utility Service area and Distribution system topology

The following figures provide an overview of the chosen Vattenfall / Finland distribution system scenario:



Vattenfall / Finland distribution system service area:





The Vattenfall / Finland service area and distribution system topology is approximated by the following more specific scenario data in Table 4.1-1. This data is then used for LTE network traffic dimensioning according to the methodology as per Fig. 3-1.

The provided numbers are not exact, but should be in the right ballpark in order to derive representative area densities for meters and RTUs. Compared to the rural area, the margin of error in these assumptions is certainly larger for urban and suburban areas due to their small size and high power density.

Table 4.1-1

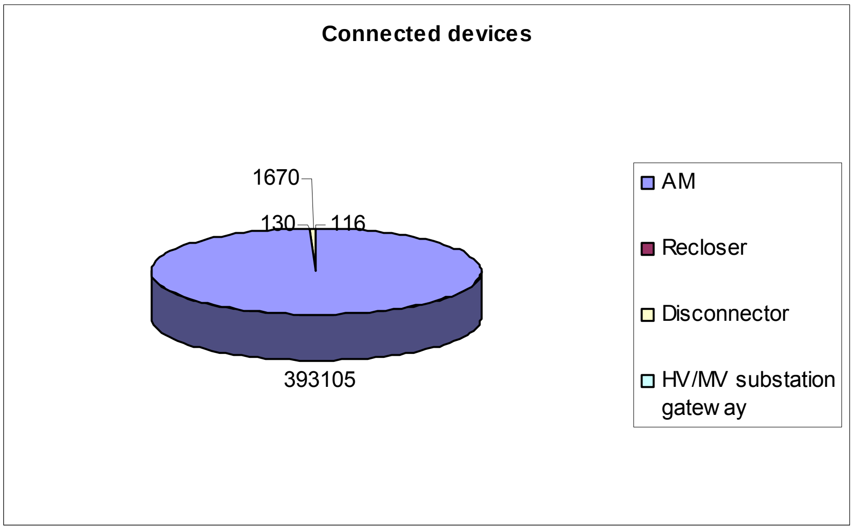
Utility service area						
	Urban	**Suburban**	**Rural**	**Total**		**Remarks**
Area, %	0.19	2.34	97.47	100.00	%	
Area, km^2	**94.1**	**1147.2**	**47758.7**	**49000**	**km^2**	**49000**
Power System Topology						
	Urban	**Suburban**	**Rural**	**Total**		**Remarks**
HV/MV substations	13	20	104	137		137
HV/MV substation area	7.2	57.4	459.2		km^2	
MV feeders / substation	8	6.5	6			
MV feeders	104	130	624	858		
Length per MV feeder	4	9	33		km	
Length of MV feeders	416	1170	20592	22178		22050
MV/LV transformers / MV feeder	6.1	13.5	30.5			
MV/LV transformers	634.4	1755	19032	21421.4		21523
MV/LV transformer density	6.7	1.5	0.4		trafos/km^2	
LV feeders / MV/LV transformer	4	3.5	3			
LV feeders	2537.6	6142.5	57096	65776.1		
Length per LV feeder	0.24	0.39	0.615		km	
Length of LV feeders	609.0	2395.6	35114.0	38118.6	km	38253
customer sites / LV feeder	20.5	13.7	4.5			
customer sites / MV/LV transformer	82	48	14			
customer sites / MV feeder	500	647	412			
customer sites / HV/MV substation	4002	4208	2471			
customer sites within area	52021	84152	256932	393105		394722
customer site density	552.65	73.35	5.38		cust/km^2	8.06
customer peak power (average)	6.5	5.5	3.0	4.00	kW	peak hour load / customer (rough estimate, averaged over all services)
power density (calculated)	3.592	0.403	0.016		MW/km^2	
power density (actual)	3.592	0.403	0.016		MW/km^2	
req MV/LV transformer rating	1066.0	527.5	81.0		kVA	50% loaded
req HV/MV transformer rating	37.2	33.1	10.6	16.41	MVA	70% loaded, average 17 MVA
fraction 3-phase / 1-phase customer sites	0.9	0.9	0.9			most alarms can only come from 3-phase AM

Clearly, the Vattenfall / Finland service area is pre-dominantly of rural type with no major cities included.

In rural areas there is very little potential for AMR traffic concentration due to an average of only 14 customer sites per MV/LV transformer and the relatively long LV feeder lengths. This is the reason for VFV focus on cellular GPRS as the primary meter access technology without relying on PLC or RF mesh traffic concentration.

Data about the number and densities of connected field devices is as follows:

AMR						
AM	52021	84152	256932	393105		100% AM penetration
AM density	552.65	73.35	5.38		AM / km^2	
% of AM behind concentrator modem	30	20	0		%	
AM / concentrating modem	15	15	1			Iskra P2CC RS-485 'concentrating' modem handles meter COSEM traffic transparently => no data storing or protocol conversions
concentrating modems	1040	1122	0	2162		
directly connected AM	36415	67322	256932	360668		
MV Feeder automation						
	Urban	**Suburban**	**Rural**	**Total**		**Remarks**
Gateway for HV/MV substations backup comm's	3	9	104	116		
Gateway density	0.0319	0.0078	0.0022		gateway/km^2	
Recloser RTUs	0	30	100	130		
Recloser RTU density	0.0000	0.0262	0.0021		RTU/km^2	
Disconnector RTUs	20	300	1350	1670		
Disconnector RTU density	0.21	0.26	0.03		RTU/km^2	
Connected field devices						
				Total		**Remarks**
# of connected radio modems in the field				364747		Subscriptions



The meter population strongly dominates over RTUs from DA.

4.2 Fault frequencies

Faults are linked to communication events such as alarms or meter queries. These event frequencies will be later related to MV fault frequencies which are considered therefore first.

4.2.1 MV Fault statistics from 2010

The following figures copied from [11] provide MV faults / 100 km as an average across most Finnish distribution system companies (not just VFV).

Fig. 4.2.1-1. MV faults / 100 km / a (from [11])

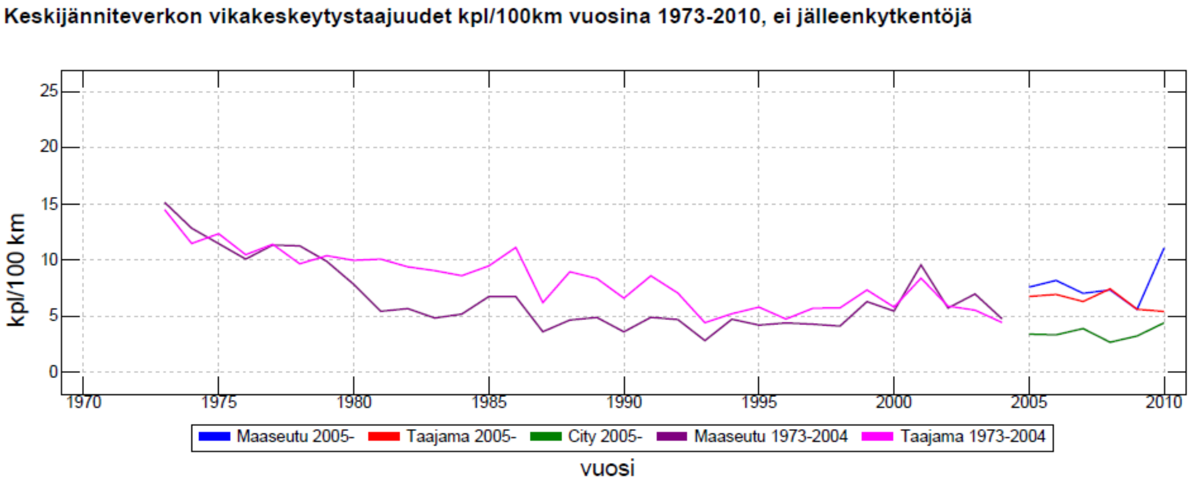
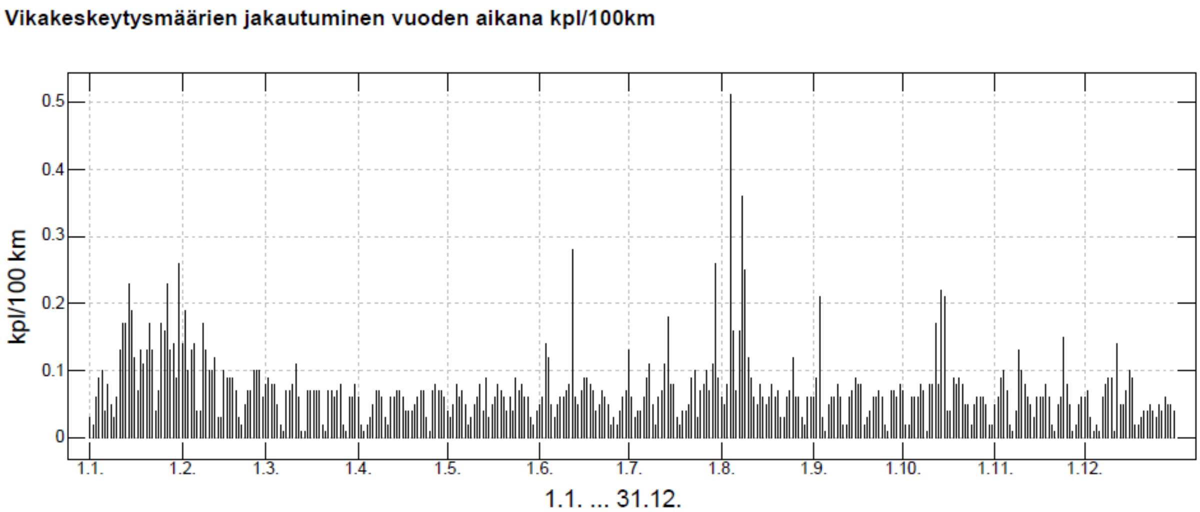
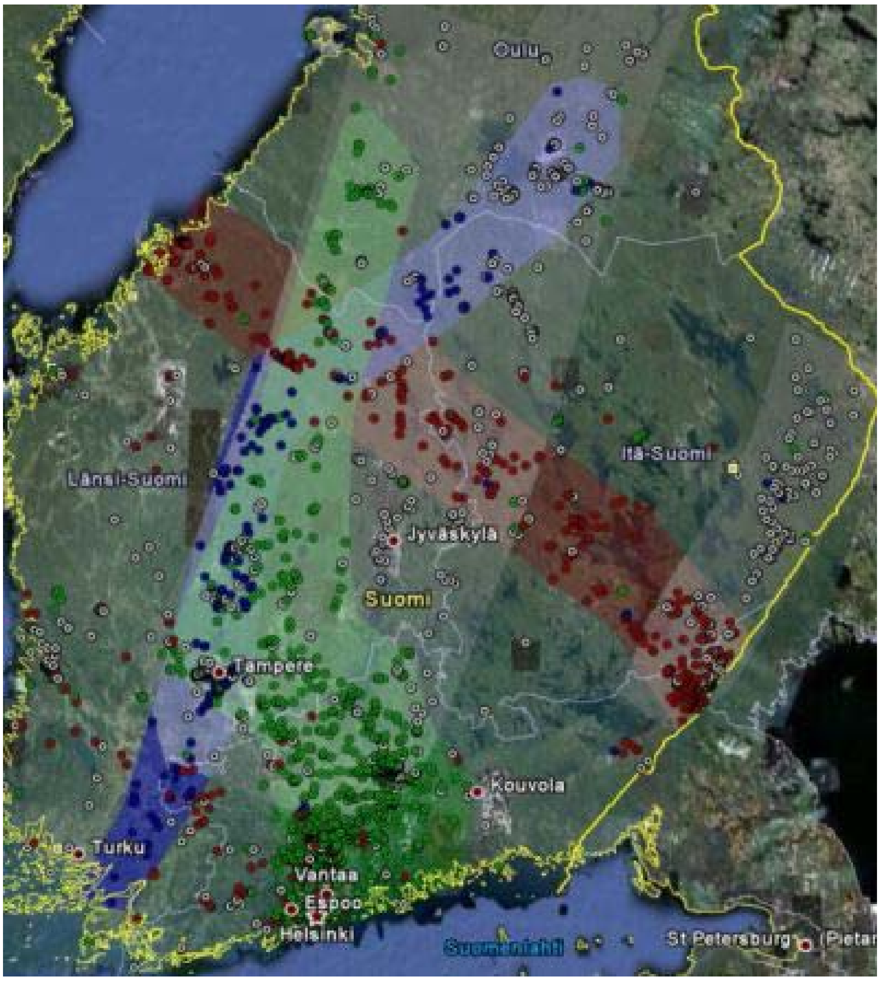
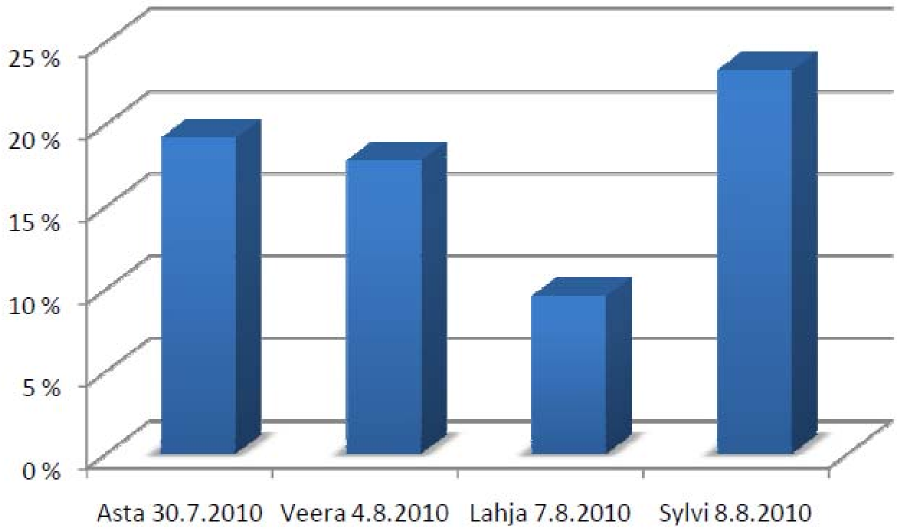


Fig. 4.2.1-2. MV faults / 100 km / d (from [11])



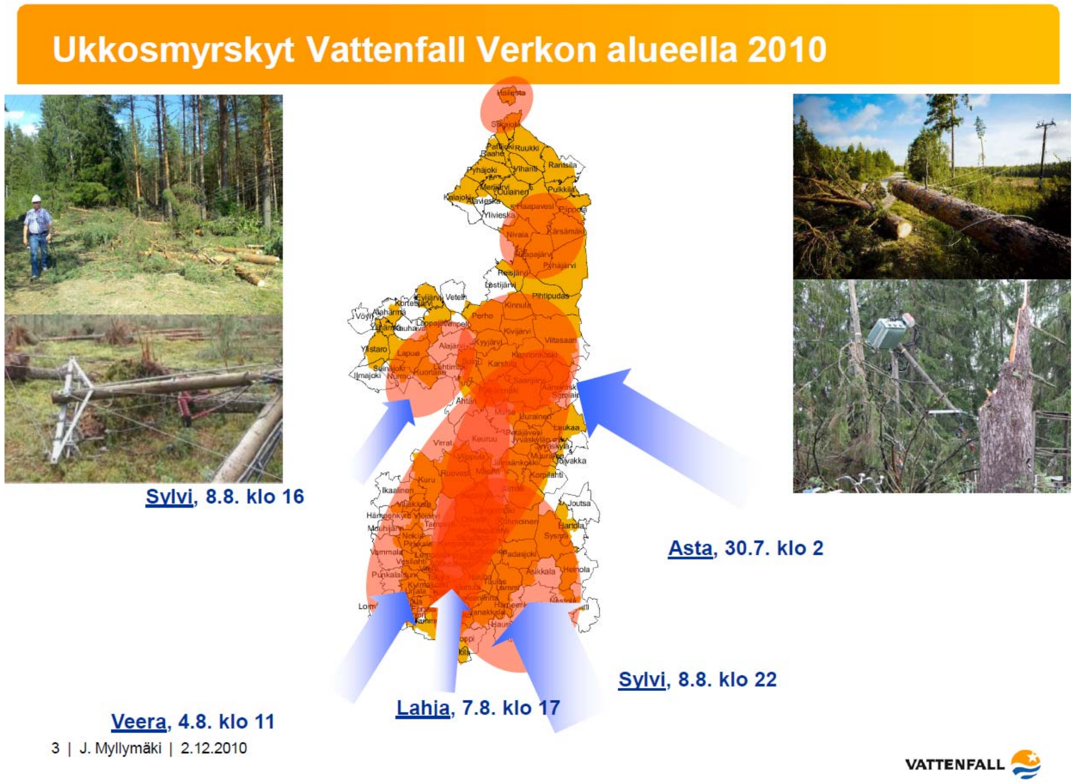
The peaks around beginning of August (4-9.8) were due to severe storms. A summary of the storm impact can be found in [10] from which also the next 2 figures are taken:

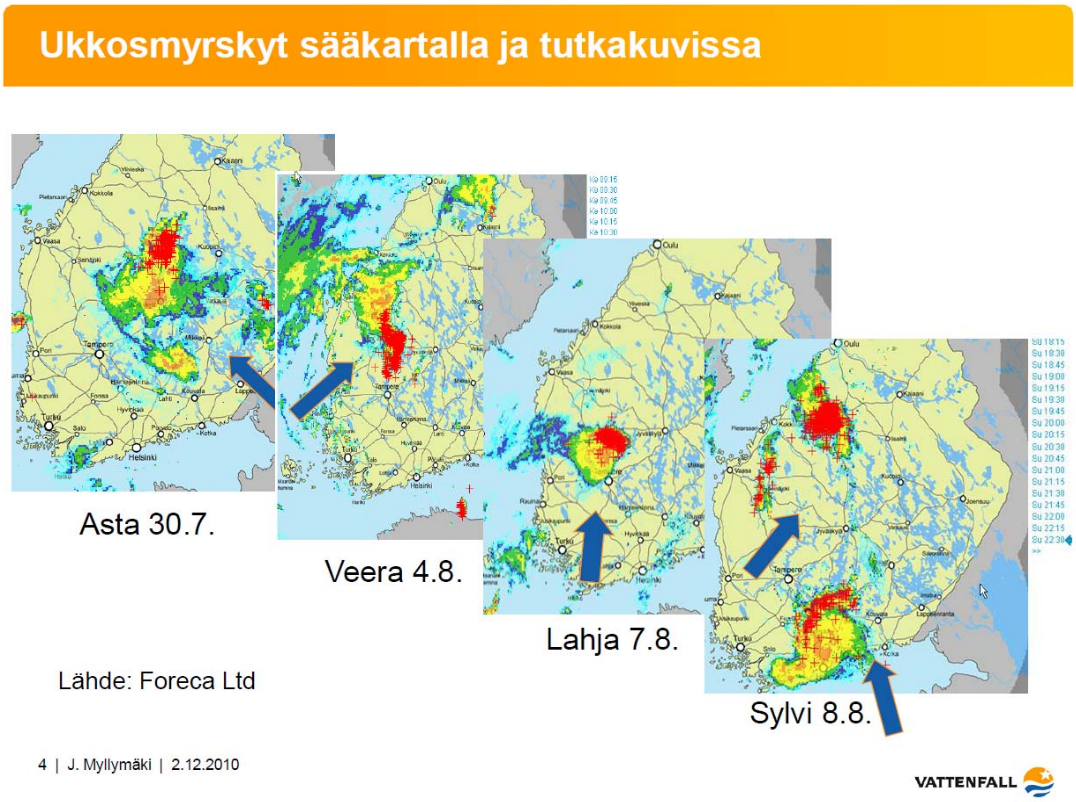


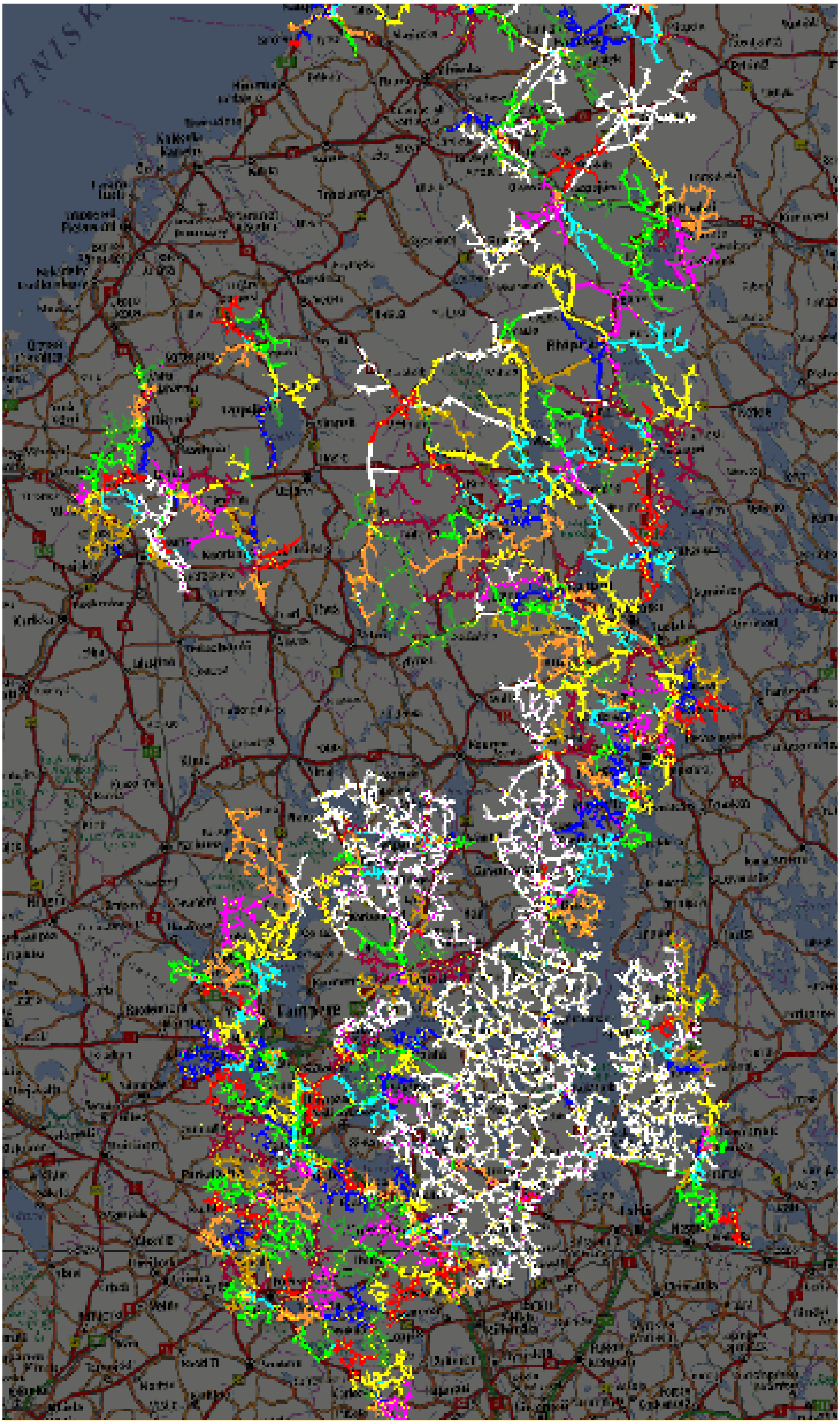


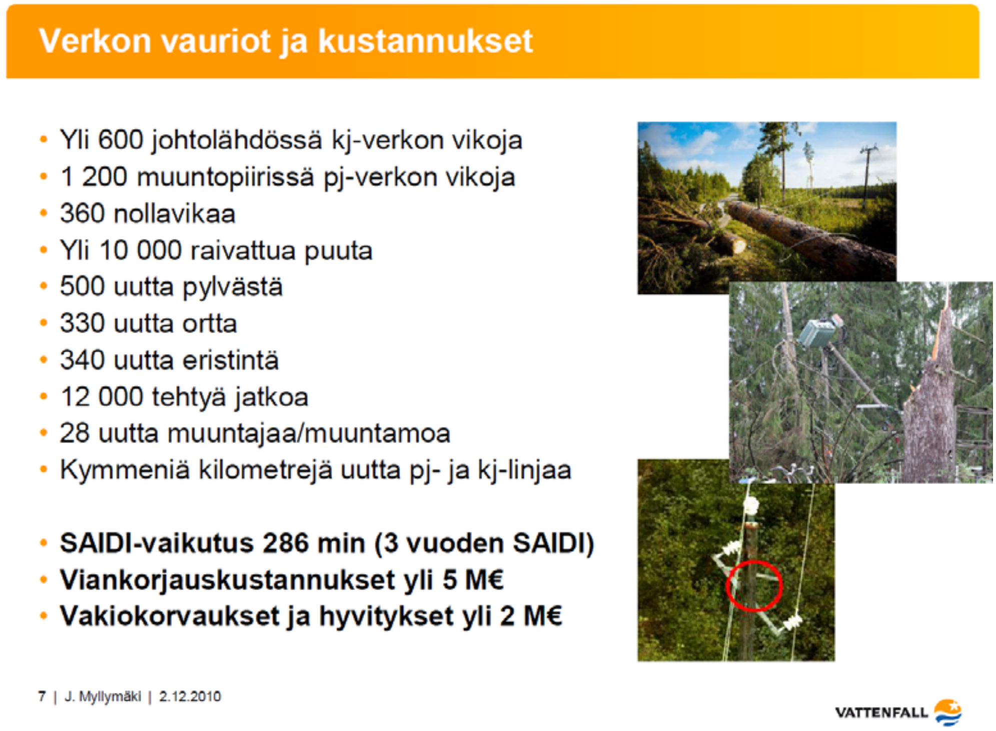
Kuva 2. Kesän 2010 myrskyjen jakautuminen kyselyyn vastanneilla verkonhaltijoilla.

The following slides borrowed from [9] describe in more detail the impact on the VFV distribution network:



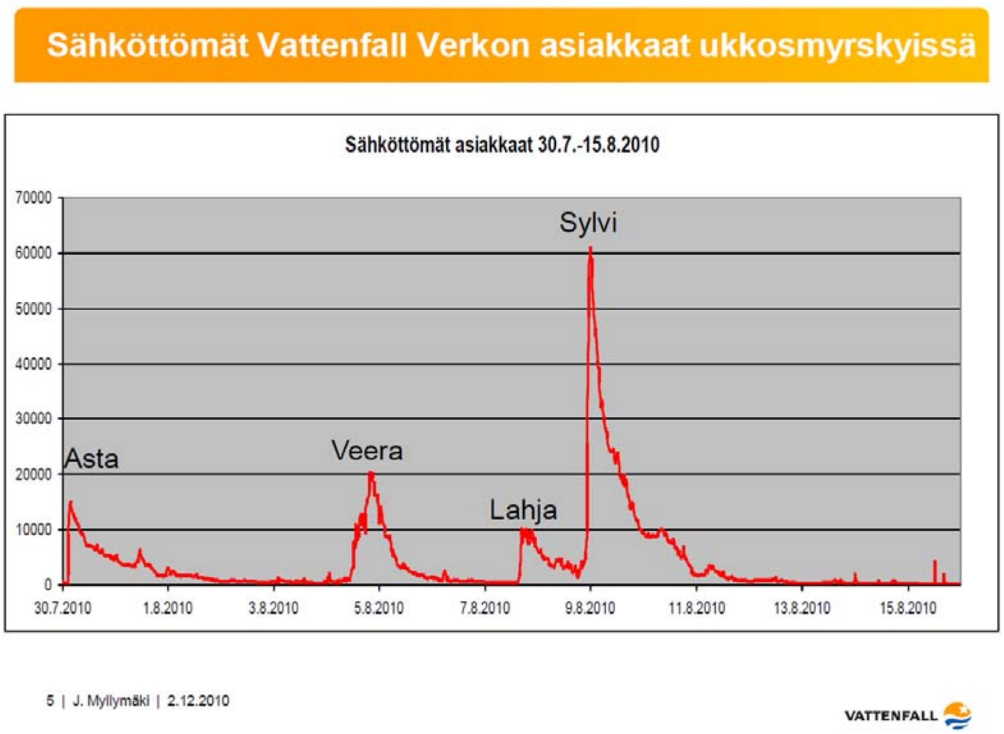






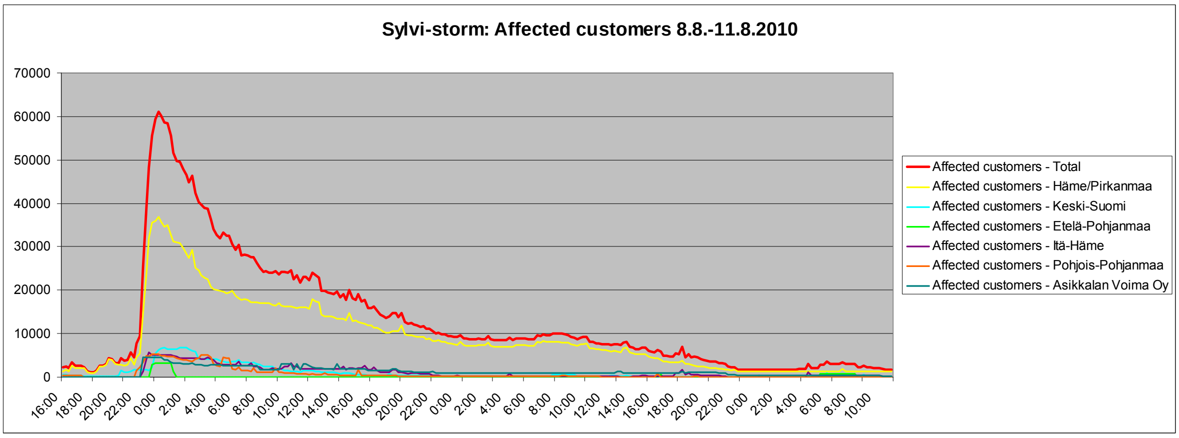
The following slides, also borrowed from [9], will show increasingly more detail about the worst storm for VFV – Sylvi.

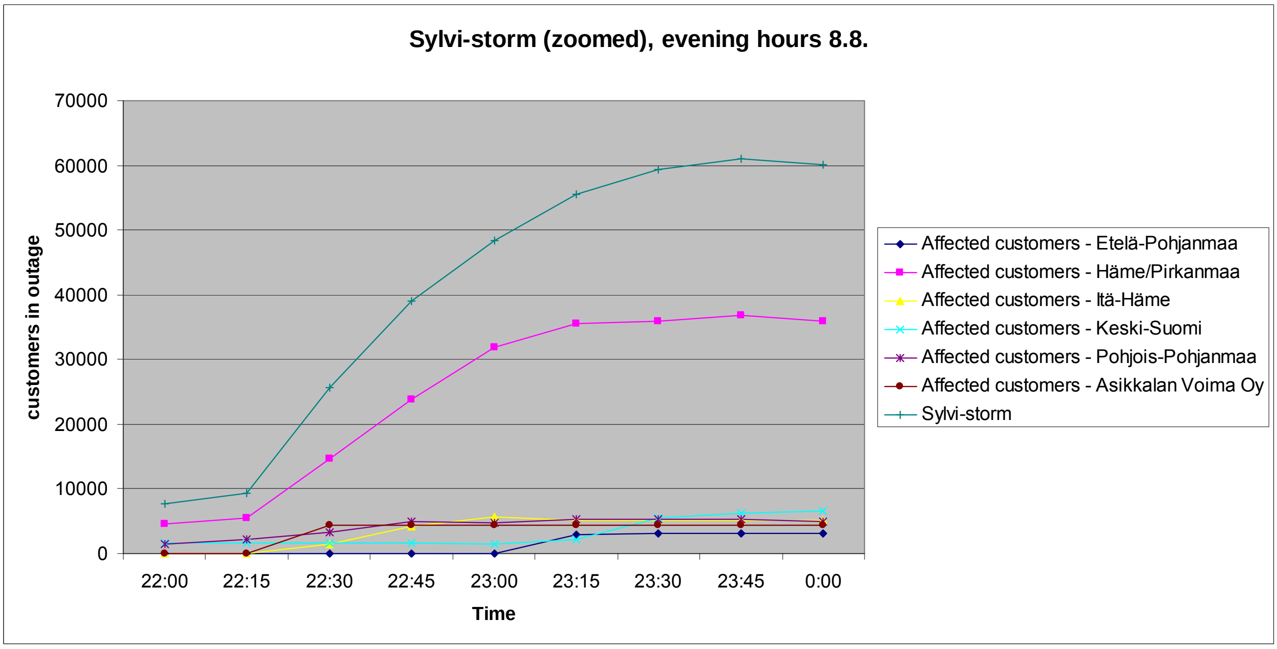
Fig. 4.2.1-3. Customer outages (from [9])



The progression of customer outages during Sylvi is shown more clearly in Fig. 4.2.1-4:

Fig. 4.2.1-4. Sylvi induced customer outages





4.2.2 MV Fault frequencies

From the data in section 4.2.1 we will derive MV fault frequencies as follows:

Yearly average MV fault frequency: for rural area Fig. 4.2.1-1 shows around ~11.1 MV faults / 100 km / a, however, this is an average across nearly all distribution system operators in Finland of which 65% were not affected by the storms [10]. Assuming for the unaffected distribution system operators 7.5 MV faults / 100 km / a, i.e. a value close to the average over the last years, we obtain for the other 45% of distribution system operators affected by the storms an adjusted value around 15.5 MV faults / 100 km / a, i.e. ~1.4x the values from Fig. 4.2.1-1. This results for the VFV area in

Yearly average fault frequency (2010)					
	Urban	Suburban	Rural	Total	
MV faults / 100 km / a	6.3	7	15.5		f / 100 km / a
MV faults / a	26.2	81.9	3191.8	3299.9	f / a
MV faults / h	0.003	0.009	0.364	0.377	f / h

However, storms tend to make the fault event rate rather 'peaky', i.e. non-uniformly distributed in both time and (geographical) area domain. We will consider hourly peak MV fault frequencies.

Hourly peak MV fault frequency, within whole system area, during Sylvi storm:

A. From Fig. 4.2.1-4. we find at 22:15 the highest rate of power outages of 15000 outages / 15 min, i.e. 45000/h across the VFV system. Table 4.1-1 shows 412 customers per rural feeder which have on average ~2 disconnectors which results in a lower number of customers in outage per MV fault; let us assume here 275 instead of 412. This gives a rate of 45000/275 = ~164 MV faults/h.
B. VFV quoted 600 MV faults due to storms of which ~57% or 342 faults are due to Sylvi by inspection of Fig. 4.2.1-3. From Fig. 4.2.1-2 we see that around 50% or 171 of the Sylvi induced faults occurred in the evening of 8.8., the remaining ones during the following 2 days. Fig. 4.2.1-4. shows that 90% of these 171 faults occurred between 22:15 and 23:15, i.e. within 1 h or at a rate of ~154 MV faults/h.
C. Fig. 4.2.1-4 shows for the 8.8 ~0.36 MV faults/100 km/d averaged across all distribution system operators in Finland. However, according to [10] only 21% of the distribution system operators were affected by Sylvi, so this value should be adjusted upwards by a factor of 2.3 resulting in ~0.83 MV faults/100 km/d or for the rural VFV area 170.6 faults. Assuming 90% of these within 1 h gives a rate of ~153.5 MV faults/h.

These results are well aligned and summarized as:

Hourly peak fault frequency, within whole system area, during Sylvi storm					
	Urban	Suburban	Rural	Total	
Peak-to-Average Event Rate (time) PAER_time	431	431	431		
peak MV faults / h	1.29	4.03	157	162.32	f / h

During the worst hour of Sylvi the Peak-to-Average Event (=fault) Rate increased in the time domain by a factor of ~431 compared to the yearly average.

However, storms tend to make the fault event rate also non-uniformly distributed in the (geographical) area domain which needs to be considered when computing cell peak loads.

Hourly peak MV fault frequency, within affected area, during Sylvi storm:

Fig. 4.2.1-4 shows that during the worst hour of Sylvi around 35500 or 65% of the faults occurred in Häme/Pirkamaa region alone. From the above figure of MV feeders in outage we can roughly estimate that about ½ of the Pirkamaa region and most of "Päijät-Häme" were affected, together that is ~14500/2 + 6200 = 13450 km^2 or 27% of the VFV area. This gives an area Peak-to-Average non-uniformity factor of 0.65*49000/13450 = 2.37.

Hourly peak fault frequency, within affected area, during Sylvi storm					
	Urban	Suburban	Rural	Total	
Peak-to-Average Event Rate (area) PAER_area	2.37	2.37	2.37		
Peak-to-Average Event Rate (time and area) PAER_time_area	1021.2	1021.2	1021.2		
peak MV faults / h	3.06	9.55	372.09	384.69	f / h

During the worst hour of Sylvi the Peak-to-Average Event (=fault) Rate increased in the storm affected area by a factor of ~1000 compared to the yearly average.

These values for MV fault frequencies and Peak-to-Average Event Rates (PAER) will be used in the subsequent sections to derive proportional communication event rates, i.e. for those events which are triggered by a fault (alarms, tele-control).

4.2.3 Fault frequencies (LV, MV broken connector)

All MV faults are assumed to follow the Peak-to-Average Event Rates (PAER) established in the previous section.

LV faults: Around 1200 or ~30% of the LV faults occurred during the storms, out of a total around 4000 / a. Similarly to the last section point B. we assume, that of these 1200 faults around 0.57*0.5*0.9 = ~26 % occurred during Sylvi's most destructive hour, i.e. ~307 faults / h. The dominating LV fault is one phase missing.

The average and Sylvi 'busy-hour' fault frequencies and their corresponding Peak-to-Average Event Rates (PAER) are summarized as follows:

Yearly average fault frequency (2010)	% of MV faults	Urban	Suburban	Rural	Total	
Customer outage notice	220	57.7	180.2	7021.9	**7259.7**	f / a
LV zero conductor fault	12	3.1	9.8	383.0	**396.0**	f / a
LV one phase missing	125	32.8	102.4	3989.7	**4124.8**	f / a
LV voltage level	5	1.3	4.1	159.6	**165.0**	f / a
MV broken conductor	1.5	0.4	1.2	47.9	**49.5**	f / a
MV remaining faults	98.5	25.8	80.7	3143.9	**3250.4**	f / a

Hourly peak fault frequency, within whole system area, during Sylvi storm	Urban	Suburban	Rural	Total		PAER_time	PAER_area
Customer outage notice	4.4	13.9	540.3	**558.6**	f / h	674.1	2.4
LV zero conductor fault	0.2	0.8	29.5	**30.5**	f / h	674.1	2.4
LV one phase missing	2.5	7.9	307.0	**317.4**	f / h	674.1	2.4
LV voltage level	1.50E-04	4.67E-04	1.82E-02	**1.88E-02**	f / h	1.0	1.0
MV broken conductor	0.0	0.1	2.4	**2.4**	f / h	430.9	2.4
MV remaining faults	1.3	4.0	154.6	**159.9**	f / h	430.9	2.4

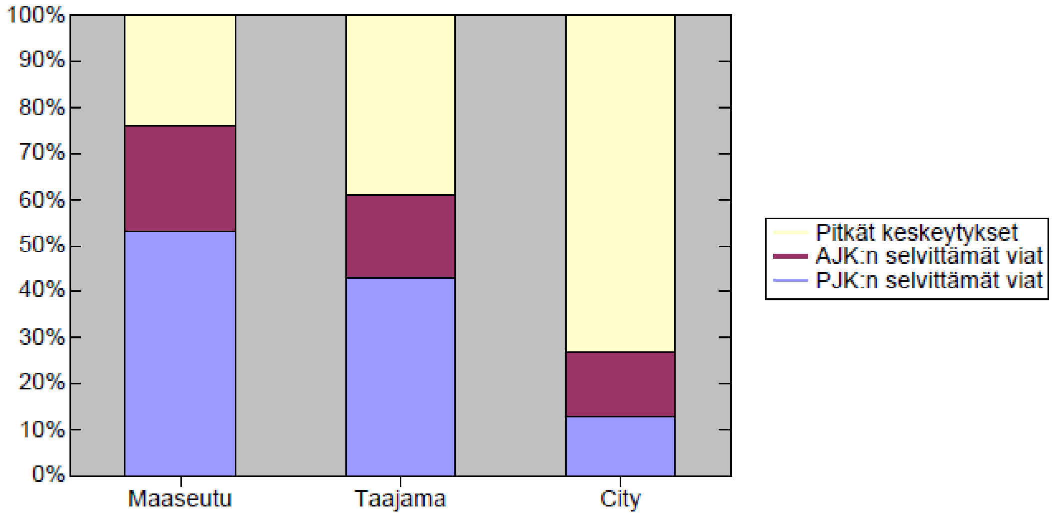
4.2.4 Reclosing

Intermittent faults cleared by reclosing are not included in the above MV (permanent) fault frequencies; however, they do cause communications events such as fault current alarms and switching state indications.

The following statistics from [11] connects reclosing events to permanent faults:

7.1 Pika- ja aikajälleenkytkentöjen selvittämät viat kaikista vikakeskeytyksistä

	Maaseutu	Taajama	City
PJK:n selvittämät viat	53%	43%	13%
AJK:n selvittämät viat	23%	18%	14%
Pitkät keskeytykset	24%	39%	73%



For the following calculation it is assumed that there is exactly one recloser per MV feeder. Reclosers can be located on poles along the feeder or at the HV/MV substation. As the communication media and routes may differ, we distinguish both cases. Reclosing along the feeder is thus proportional to (# of reclosers / # of MV feeders).

The detailed assumptions, together with the triggered events are as follows:

Table 4.2.4-1

Reclosing and Fault Isolation		Urban	Suburban	Rural	Total			Remarks
Statistics 2010								from ET
successful HSR		0.13	0.43	0.53		%		
successful DR		0.14	0.18	0.23		%		
permanent faults		0.73	0.39	0.24		%		
Reclosing events								
HSR		**35.0**	**175.2**	**8819.5**	**9029.7**	f / a		3 alarms (OC + open + close)
along feeder (pole mounted)		0.0	40.4	1413.4	**1453.8**	f / a		
at HV/MV substation		35.0	134.8	7406.1	**7575.9**	f / a		
DR		**30.5**	**99.9**	**4145.1**	**4275.5**	f / a		3 alarms (OC + open + close)
along feeder (pole mounted)		0.0	23.0	664.3	**687.3**	f / a		
at HV/MV substation		30.5	76.8	3480.9	**3588.2**	f / a		
unsuccessful DR		**26.2**	**81.9**	**3191.8**	**3299.9**	f / a		2 alarms (OC + open)
along feeder (pole mounted)		0.0	18.9	511.5	**530.4**	f / a		
at HV/MV substation		26.2	63.0	2680.3	**2769.5**	f / a		
Permanent faults. Isolation with r.c. disconnectors		26.2	81.9	3191.8	**3299.9**	f / a		5 retries: 5*2=10 disconnector cmd + 5 recl cmd + 4 recl alarm + N.O. close cmd; total of 20 events

4.3 Synopsis of the selected use cases

In a first version of this report only today's use cases such as AMR, use of AMR alarms in DMS for MV/LV outage management and MV feeder automation are considered. This will establish a baseline scenario which can be verified against empirical data obtained from current communication arrangements.

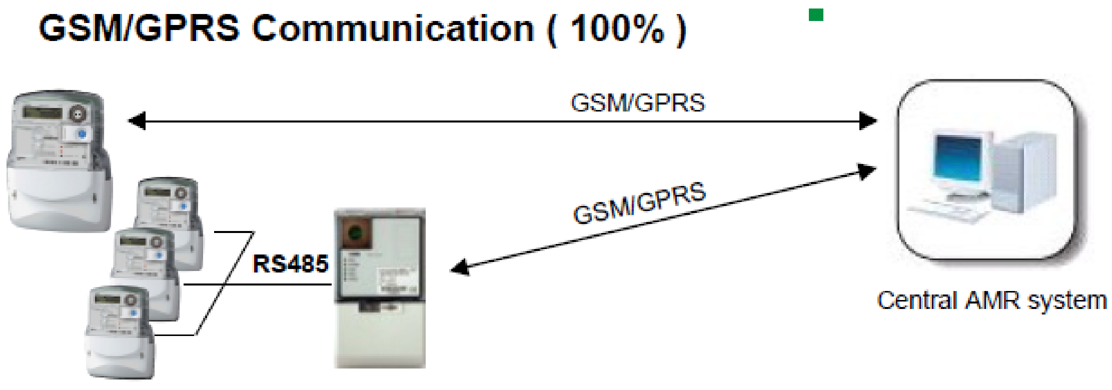
In a revised version of this report more speculative SG use cases will be added which could materialize around 2020 such as more advanced distribution automation concepts, primary substation connectivity, video surveillance, etc.

Detailed event frequencies and volumetric information are provided in Section 4.4 for the following use cases:

4.3.1 AMR

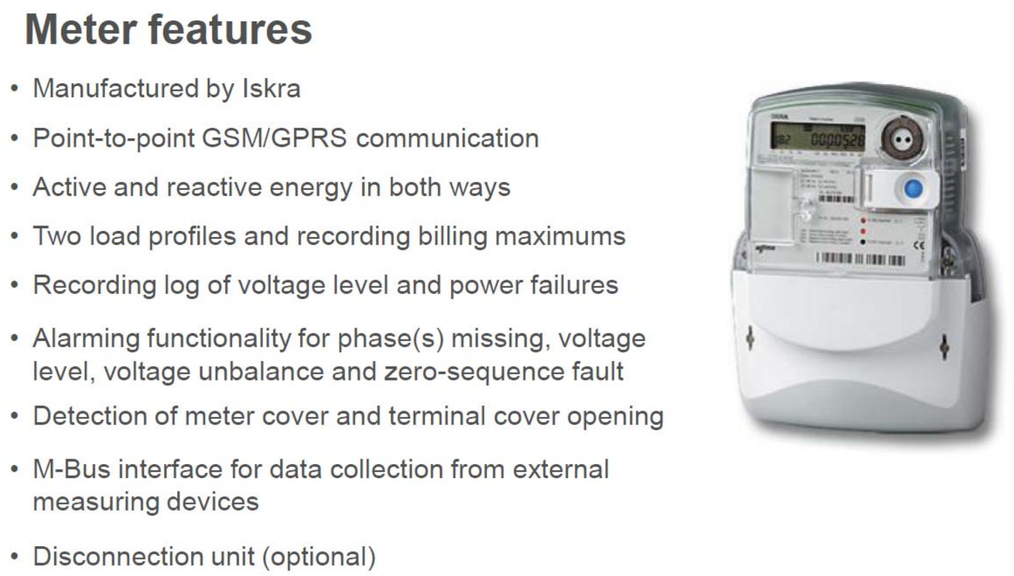
The assumed metering case is one with 100% cellular connectivity. That would be via GPRS900 today, but in the related SGEM studies LTE is assumed.

Some of the urban and suburban meters are behind a RS485 'concentrator' which we assume a 'dumb' device merely relaying the meter traffic. Nevertheless, the meter activity may be configured (coordinated) in order to bundle activity (sending reads, alarms,..) into a common RRC session. This will, however, not affect the traffic volumes which are assumed to be proportional to the amount of meters.

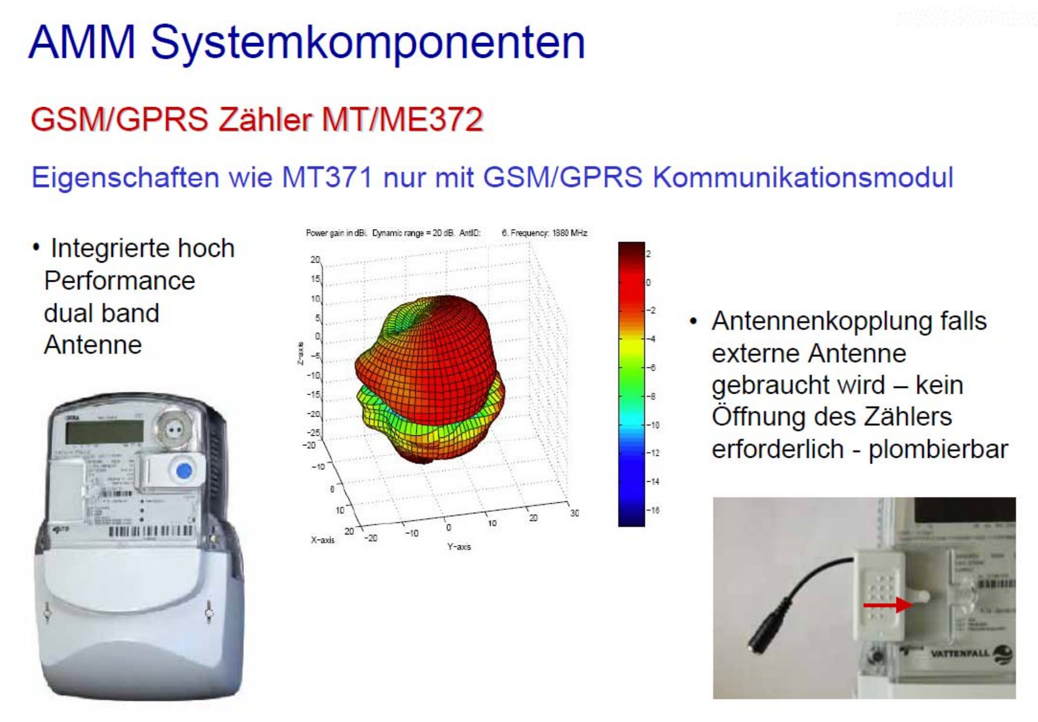


A critical parameter for AMR related traffic intensity is the duration of the time interval allocated for daily meter reads. As a baseline 6 h are assumed.

Additional information regarding the meters can be found from [7,14,15,16].



Critical parameters for coverage analysis and related site counts of dedicated utility radio networks are meter TX power, antenna gain and building penetration losses. These parameters are defined in Section 4.5.4.

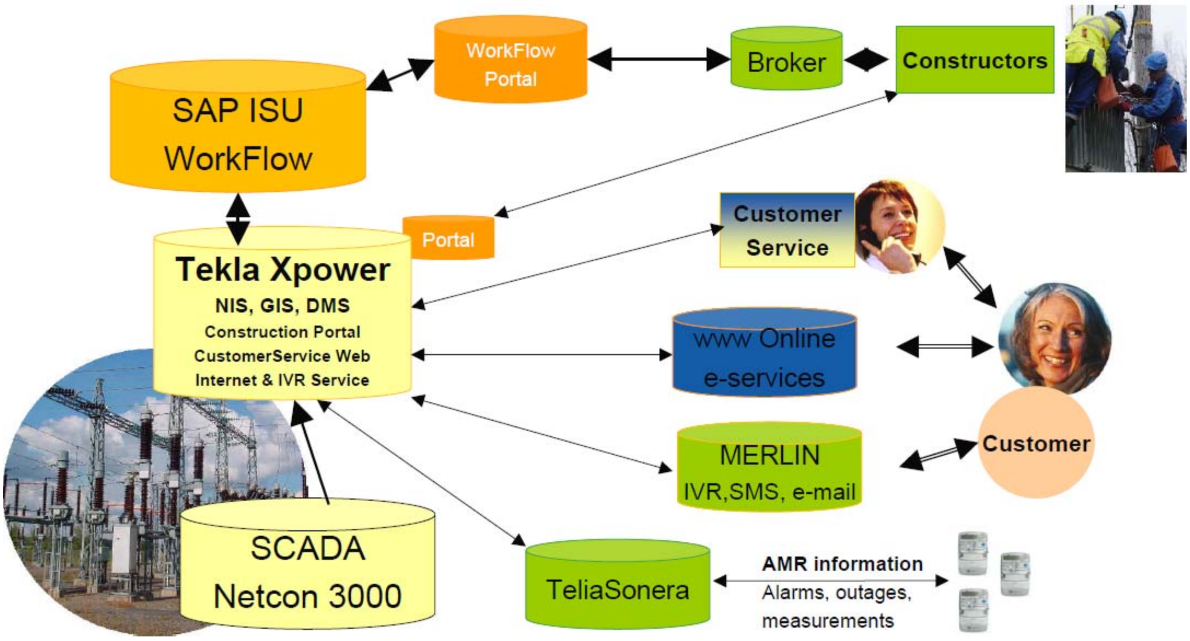


4.3.2 LV, MV Outage management with AMR + DMS

In this use case meters provide alarms to DMS as per the following architecture (see [6,7,8,19]).

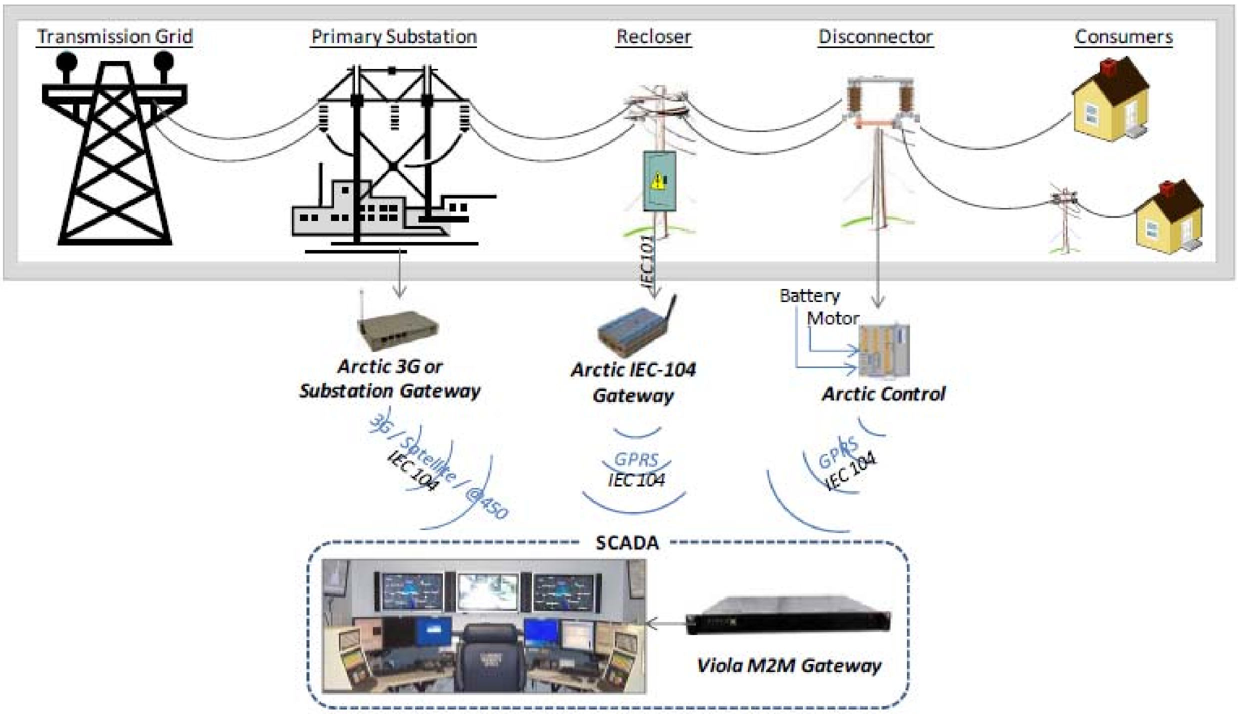
The use of meter alarms and queries are described in fairly good detail in [12] from a DMS perspective. The details of these traffic characteristics are captured in Section 4.4.

Meters are not connected via VPN tunnels, hence there is no ping base load traffic.



4.3.3 MV Feeder Automation (FA), primary substation connectivity

Background information about MV Feeder Automation (FA) can be found from [1,20]. A synopsis of the considered VFV distribution (feeder) automation use cases can be found from [17] from which the following figures are borrowed:



Network Position	Viola Systems Product	Number of Devices	Functionality
SCADA	Viola M2M Gateway Enterprise Edition	3	*Provides fixed IP addresses to all Arctic devices enabling two-way operation, as well as remote maintenance control via a VPN tunnel*
Primary substations	Arctic 3G Gateway and Arctic Substation Gateway	130	*Provides high communication capacity and availability with backup routing function*
Reclosers	Arctic IEC-104 Gateway	200	*Offers real-time remote control and monitoring, thus enabling fast fault isolation and efficient recovery from blackouts*
Disconnector stations	Arctic Control	1300	*Provides a total solution for disconnector control including motor protection, battery charging and monitoring as well heater control*

The generated IEC-104 traffic from disconnectors is dominated by battery voltage, RTU metallic enclosure ('kotelo') temperature measurements and binary state indications which are reported to SCADA when their respective values change. Reclosers additionally report MV line currents and voltages on value change. IEC-104 events and control signaling related to reclosing events are listed in Section 4.2.4. Additional base-load is generated by periodic ICMP pings within the VPN tunnel. The details of these traffic characteristics are captured in Section 4.4.

VFV's primary substations can be compact and located at remote sites with no wireline communications. Their role is to improve MV distribution network reliability by reducing MV feeder lengths. The following picture gives an impression of such a compact substation.

The generated IEC-104 traffic is dominated by reporting ~40 analog measurements and ~400 digital I/O state points to SCADA on value change (HV, MV busbar voltages, feeder currents, switching states,…). Additionally there are IEC-104 events (alarms) and control signaling, e.g. those related to reclosing (most reclosers are located at the primary substations). As of today, no disturbance files or surveillance video is transferred to SCADA, however, these might be considered as future UCs. Tele-protection related line signaling of the 110 kV sub-transmission network is handled by the national transmission operator FINGRID (fiber connectivity).

In most countries connectivity between the primary substations and SCADA / DMS is provided via wireline / fiber access. However, in VFV's case this connectivity is provided today primarily by the @450 (FlashOFDM) radio network [22] with backup connections via satellite. 3G gateways (+satellite backup routing) are used at locations with no @450 coverage. The following picture shows the related antenna installation.

FlashOFDM is considered obsolete technology making this use case interesting for LTE. In the following we assume that all traffic is transferred via LTE.


HughesNet

4.4 Event frequencies and data volume requirements of selected use cases

The list of considered events is not intended to be complete; the focus is on regular events which cause a significant baseload (e.g. meter reads, frequent IEC-104 measurement indications, VPN tunnel pings,…) or are triggered by faults and thus scale with high Peak-to-Average factors during storms.

Not included are exceptional events related to e.g.

- outages of the VPN connections (PDP context timer expiry, changeover from M2M GWs, IEC-104 General Interrogations, VPN connection parameter re-negotiations,…)
- failures of the telco equipment itself (eNB, EPC, M2M GW,…) which could lead to a larger number of connection re-establishment requests of the field devices within short periods of time.

The following event frequencies and data volumetrics are based on relatively rough estimates; they are not an outcome from empirical data of the actual traffic. They are therefore approximations and it is expected that some future additions and corrections of the event related parameters might be needed in order to tune the scenario better towards the actual aggregate communication data volumes.

In fact, some difficulty was encountered to match the calculated event-based FA and substation related traffic to some of the measured aggregate data volume points obtained from the actual network. The calculated traffic is ~2.5 … 4x smaller than actual measured traffic which might be due to the missing overheads from VPN connection re-establishments, possibly wrongly configured field RTUs with high reporting or ping rates etc. Nevertheless, while this error sounds large, it has little impact on the overall conclusions and can be accepted for the time being. Significantly more work would be required to obtain detailed data from the two underlying GPRS networks for better calibration; moreover to resolve the data volume on the granularity of individual events also measurements from SCADA/DMS and the AMR MDMS would be required.

4.4.1 Mapping of Faults to Events, Event frequencies

A number of events scale with fault frequencies, however, not all of them such as IEC-104 measurements or RTU pings.

The current assumptions regarding the list of events together with their yearly occurrences <u>for the whole distribution network</u> (i.e. sum over all field devices) are captured in Table 4.4.1-1.

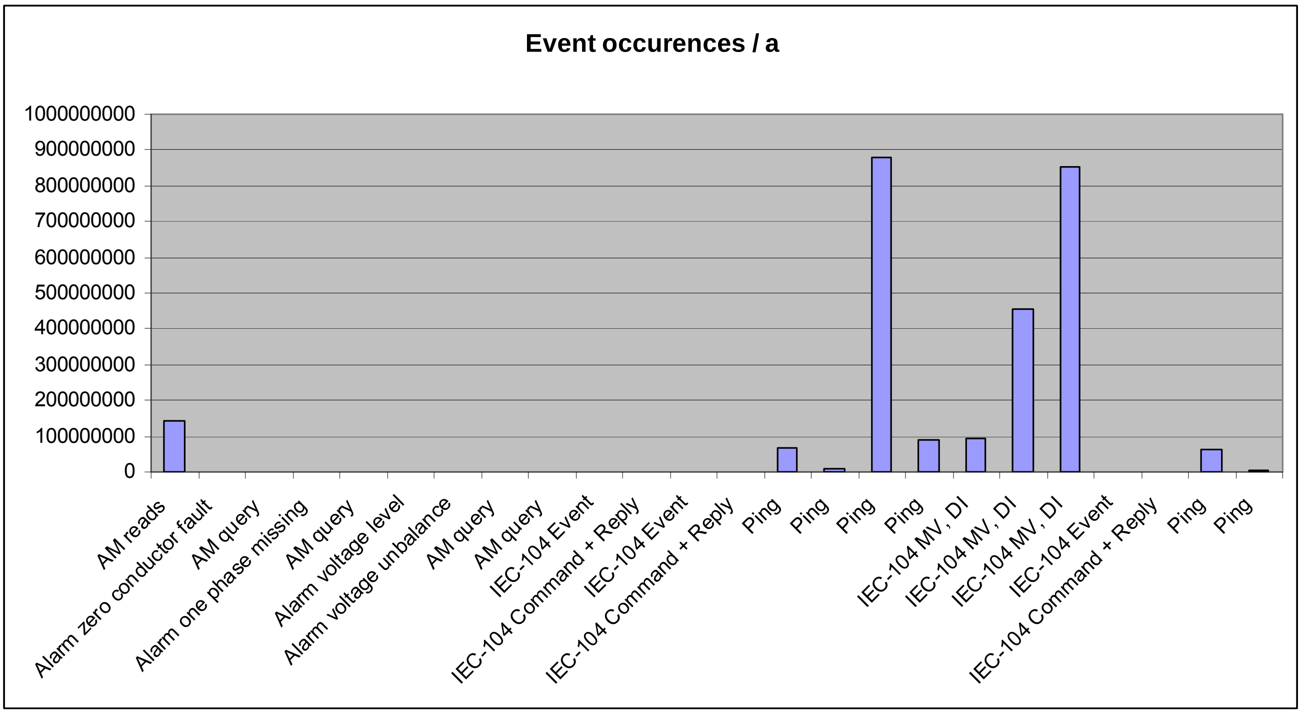
The rationale for event frequencies is captured in the ‘Remark’ column. The recloser related IEC-104 events are accumulated from the # of alarms and commands as provided in Table 4.2.4-1.

Also the Peak-to-Average Event Rates (PAER) multipliers for scaling event rates e.g. under storm conditions or AMR activity are provided.

Table 4.4.1-1

				Urban	Suburban	Rural	Total				
Events & frequencies	Use case	Field device	EPC transactions	Events / a	Events / a	Events / a	Events / a	Remarks	PAER_BH	PAER_sec	PAER_area
AM reads	AMR	AM	RRC	18987592	30715571	93780180	**143483343**	AM reads uniformly over 6 h, spatially uniform	4.0	1	1.0
Alarm zero conductor fault	AMR+DMS	AM	RRC	29	61	776	**865**	1/2 of the AM on LV feeder send alarm	674.1	1	2.4
AM query	AMR+DMS	AM	PAG_RRC	29	61	776	**865**	the other half is queried after zero conductor fault alarm	674.1	1	2.4
Alarm one phase missing	AMR+DMS	AM	RRC	302	631	8079	**9012**	1/2 of the AM on LV feeder send alarm	674.1	1	2.4
AM query	AMR+DMS	AM	PAG_RRC	302	631	8079	**9012**	the other half is queried after one phase missing alarm	674.1	1	2.4
Alarm voltage level	AMR+DMS	AM	RRC	66	265	6571	**6902**	1/10 of the AM on MV feeder send alarm	1.0	1	1.0
Alarm voltage unbalance	AMR+DMS	AM	RRC	88	358	8871	**9317**	1/2 of the AM on MV feeder send alarm	430.9	1	2.4
AM query	AMR+DMS	AM	PAG_RRC	726	2937	72815	**76479**	6.25% of AM on MV feeder are queried after MV fault. During storm repairs time are stretched over 24 h	18.0	1	2.4
AM query	AMR+DMS	AM	PAG_RRC	957	1999	25595	**28552**	90% of AM on the same LV feeder are queried after customer outage notice	674.1	1	2.4
IEC-104 Event	FA	Recloser	RRC_CONN	0	556	20023	**20579**	see description 'Reclosing events'	430.9	1	2.4
IEC-104 Command + Reply	FA	Recloser	RRC_CONN	0	410	15959	**16368**	see description 'Reclosing events'	430.9	1	2.4
IEC-104 Event	FA	Disconnector	RRC	0	0	0	**0**	TBD;reserved	430.9	1	2.4
IEC-104 Command + Reply	FA	Disconnector	PAG_RRC	288	901	35109	**36299**	see description 'Reclosing events'	430.9	1	2.4
Ping	FA	Recloser	RRC_CONN	0	15768000	52560000	**68328000**	ICMP echo req within VPN tunnel, 1 per min	1.0	1	1.0
Ping	FA	Recloser	RRC_CONN	0	1576800	5256000	**6832800**	ICMP echo req within VPN tunnel, 1 per 10 min	1.0	1	1.0
Ping	FA	Disconnector	RRC	10512000	157680000	709560000	**877752000**	ICMP echo req within VPN tunnel, 1 per min	1.0	1	1.0
Ping	FA	Disconnector	PAG_RRC	1051200	15768000	70956000	**87775200**	ICMP echo req within VPN tunnel, 1 per 10 min	1.0	1	1.0
IEC-104 MV, DI	FA	Recloser	RRC_CONN	0	22075200	73584000	**95659200**	84 measurements / h	1.0	1	1.0
IEC-104 MV, DI	FA	Disconnector	PAG_RRC	5468160	82022400	369100800	**456591360**	32 measurements / h	1.0	1	1.0
IEC-104 MV, DI	SS_CONN	GW_SS	RRC_CONN	22075200	66225600	765273600	**853574400**	14 measurements / min	1.0	1	1.0
IEC-104 Event	SS_CONN	GW_SS	RRC_CONN	354	1088	50788	**52231**	see description 'Reclosing events'	430.9	1	2.4
IEC-104 Command + Reply	SS_CONN	GW_SS	RRC_CONN	131	410	15959	**16499**	see description 'Reclosing events'	430.9	1	2.4
Ping	SS_CONN	GW_SS	RRC_CONN	1576800	4730400	54662400	**60969600**	ICMP echo req within VPN tunnel, 1 per min	1.0	1	1.0
Ping	SS_CONN	GW_SS	RRC_CONN	157680	473040	5466240	**6096960**	ICMP echo req within VPN tunnel, 1 per 10 min	1.0	1	1.0
Total / a				5.983E+07	3.970E+08	2.200E+09	**2.657E+09**				
Total / h				6.830E+03	4.532E+04	2.512E+05	**3.033E+05**				
Total / s				1.897E+00	1.259E+01	6.978E+01	**8.426E+01**				

The yearly event occurrences from Table 4.4.1-1 are visualized in the following chart. The dominating events are IEC-104 measurement and state indications from RTUs and primary substation, RTU VPN pings and AM reads. In comparison fault related alarms and commands are not significant.



4.4.2 Event communication volumetric data

TCP/IP and 3GPP protocol overhead parameters relevant for air-interface capacity are summarized in the following table:

TCP/IP and 3GPP protocol overhead parameters		
IP MTU	1400	Bytes
IP+TCP,UDP headers	40	Bytes
LTE RRC connection establishment overhead (C-plane)	425	Bytes
TCP/IP connection establishment overhead (U-plane)	160	Bytes
VPN overhead	60	Bytes
LTE PDCP+RLC overhead factor (between MAC and IP)	1.06	

SSH-VPN overheads are included for the FA and primary substation ‘always-on’ connections.

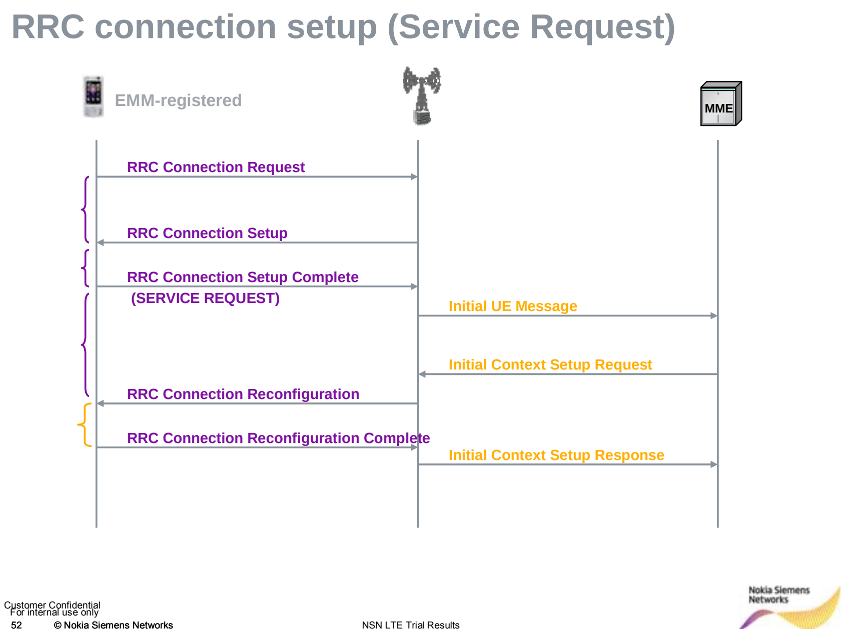
It is assumed that all field devices are MME registered (“attached”) and have already the required PDN connection and default bearer established.

Overhead related to TCP/IP connections establishment & release is included for meters. RTUs and substation GW are assumed to have an active VPN tunnel connection.

Furthermore, it is assumed that each event related to meters or disconnectors will lead to a transition from RRC_IDLE to RRC_CONNECTED state (see following Figure) and then back to RRC_IDLE. This tacitly assumes that the RRC release timer is set shorter than the average gap between subsequent events within a RRC connection which appears to be a reasonable assumption for the considered use cases. Frequent pings to monitor the VPN tunnels to/fro disconnector RTUs can lead to large signaling overhead from the RRC state transitions. Therefore this overhead is accounted for in the load calculations.

On the other hand, recloser RTUs and substation GWs have inter-event distances which are smaller than typical RRC release timer values, therefore these connections stay in the RRC_CONNECTED state. There are relatively few recloser RTUs and substation GWs per cell, hence this is a reasonable assumption. In LTE the related radio resource consumption (e.g. control channel capacity) can be optimized by utilizing DRX for these connections.

RRC related C-plane signaling traffic and PDCP+RLC overhead is not visible in S1 interface U-plane traffic, however, here IP transport overhead (GTP, Ipsec, Ethernet) becomes relevant and is accounted for.



The current assumptions regarding the event communication volumetric data across the air-interface are captured in Table 4.4.2-1:

Table 4.4.2-1

Events & volumetrics	Use case	Field device	EPC transaction	UL Application payload [Bytes]	DL Application payload [Bytes]	UL data volume incl. protocol overheads [Bytes]	DL data volume incl. protocol overheads [Bytes]
AM reads	AMR	AM	RRC	9600	80	11092.9	1001.7
Alarm zero conductor fault	AMR+DMS	AM	RRC	100	80	768.5	747.3
AM query	AMR+DMS	AM	PAG_RRC	100	80	768.5	747.3
Alarm one phase missing	AMR+DMS	AM	RRC	100	80	768.5	747.3
AM query	AMR+DMS	AM	PAG_RRC	100	80	768.5	747.3
Alarm voltage level	AMR+DMS	AM	RRC	100	80	768.5	747.3
Alarm voltage unbalance	AMR+DMS	AM	RRC	100	80	768.5	747.3
AM query	AMR+DMS	AM	PAG_RRC	100	80	768.5	747.3
AM query	AMR+DMS	AM	PAG_RRC	100	80	768.5	747.3
IEC-104 Event	FA	Recloser	RRC_CONN	25	0	132.5	106.0
IEC-104 Command + Reply	FA	Recloser	RRC_CONN	25	20	132.5	127.2
IEC-104 Event	FA	Disconnector	RRC	25	0	583.0	556.5
IEC-104 Command + Reply	FA	Disconnector	PAG_RRC	25	20	583.0	577.7
Ping	FA	Recloser	RRC_CONN	44	44	152.6	152.6
Ping	FA	Recloser	RRC_CONN	44	44	152.6	152.6
Ping	FA	Disconnector	RRC	44	44	603.1	603.1
Ping	FA	Disconnector	PAG_RRC	44	44	603.1	603.1
IEC-104 MV, DI	FA	Recloser	RRC_CONN	70	0	180.2	106.0
IEC-104 MV, DI	FA	Disconnector	PAG_RRC	25	0	583.0	556.5
IEC-104 MV, DI	SS_CONN	GW_SS	RRC_CONN	130	0	243.8	106.0
IEC-104 Event	SS_CONN	GW_SS	RRC_CONN	25	0	132.5	106.0
IEC-104 Command + Reply	SS_CONN	GW_SS	RRC_CONN	25	20	132.5	127.2
Ping	SS_CONN	GW_SS	RRC_CONN	44	44	152.6	152.6
Ping	SS_CONN	GW_SS	RRC_CONN	44	44	152.6	152.6

The application payloads are rough estimates; they are not an outcome from empirical data of the actual traffic or from a deeper analysis of the protocols and the transmitted data content.

For IEC-104 APDUs it has been assumed that the APCI and ASDU headers consume together ~10 Bytes and that each information object consumes ~15 Bytes including time stamp. For the analog measurement indications from RTUs and primary substations it has been assumed that multiple information objects originating from the same function block are bundled within one ASDU; e.g. that the recloser RTU reports 4 current at the same time (for the 3 phases + 0-current).

A few observations:

- UL - DL asymmetry is highest for the meter reports (~11:1); for the remaining events TCP ACKs, VPN and RRC signaling overheads tend to level this difference
- VPN related overhead relative to the APDU is ~5x for IEC-104 messages with a single information object and somewhat less for APDUs with multiple information objects
- the RRC related signaling overheads (across the air-interface) are significant for small data volumes; e.g. increasing the total overhead for disconnectors relative to the IEC-104 APDU by factor ~20x

4.5 Wireless communications system parameters

4.5.1 General assumptions

In the studies within this SGEM subtask, the SG communications traffic with field devices (automatic meters, RTUs,…) is assumed to be carried exclusively wirelessly. In Europe wireless traffic from FANs is collected today pre-dominantly by public GSM900 networks. This is also the case in the above Vattenfall / Finland distribution system scenario.

M2M traffic carried today by public GSM900 networks will be shared in the nearer future with WCDMA/HSPA 2100/900 networks and in the more distant future additionally with LTE800/1800/2600 networks. Some of these networks will be implemented by CSPs with multi-radio / standard base stations serving different 3GPP radios within or across their respective frequency bands. They are built on a generic ("SW defined radio") base station and common core network platform. This 3GPP radio evolution is described in more detail in [1].

LTE has established itself in the CSP domain as the leading global standard and platform for IP optimized radio communications. All major mobile standards such as GSM, WCDMA and cdma2000 converge into the LTE IP based platform.

Also established radio standards for mission critical applications such as TETRA (for public safety), GSM-R (for life-critical train-control and railway communications) and P25 (for public safety in the US) evolve their next generation standard towards LTE/SAE. As a case in point, within the US, a strong consensus has emerged in support of LTE/SAE, as a common technology platform for the public safety broadband network. Subsequently the FCC will mandate that all networks deployed in the 700 MHz public safety broadband spectrum adopt LTE in order to facilitate nationwide interoperability for public safety broadband networks.

Therefore, there is an opportunity for utilities to join this growing ecosystem for mission critical radios based on LTE. Some utilities, notably in US, are expected migrating their current dedicated radio networks to a dedicated converged LTE IP network.

From this perspective it may be of interest within the coming FP3 of SGEM to conduct comparative studies on OPEX/CAPEX of a CSP provided vs. dedicated utility radio network. By assuming LTE in both cases we don't need to additionally translate assumptions and results across different radio technologies. Therefore we consider for the following communications system parameters both a *CSP provided 10 MHz LTE MBB network* as well as a *Dedicated 5 MHz LTE network* which has been coverage optimized for the utility. The actual ownership of the dedicated utility optimized LTE network is of no importance for the dimensioning studies here: it could be directly owned and operated by the utility or it could be owned and operated by a service provider on behalf of the utility.

In order to simplify the analysis and focus on the worst case from a loading / congestion point of view we assume in both cases that all SG traffic is aggregated into a single LTE network and frequency band. This also fits to the timeframe (up to 2020) of the considered distribution automation use cases. By 2020 CSP operated LTE networks will be more mature and can take a larger burden of the MBB and utility M2M traffic.

For the dedicated utility optimized LTE network it is interesting to know how much of the LTE capacity will be used up by the SG M2M traffic (or the other way around: how much spectrum would actually be required by the utility), the potential for congestion and OPEX/CAPEX comparisons with M2M services from CSP MBB networks.

Even though LTE is chosen in the analysis, many of the results should nevertheless also hold for comparable broadband radios such as CSP operated HSPA or utility operated WiMAX.

4.5.2 LTE channel BW, MIMO assumptions

To simplify the studies, we assume for both LTE networks FDD duplex mode. However, it needs to be kept in mind that some of the dedicated BB utility networks are operating in unpaired spectrum, e.g. 2.3 GHz WiMAX TDD networks in Australia. The LTE TDD mode is definitely of relevance for SG communications.

For the CSP provided MBB network we assume a LTE channel bandwidth of 10 MHz which is a very common deployment case. Obtaining spectrum for the dedicated utility network is a big challenge and considering also lower traffic volumes and intensity compared to MBB a smaller channel bandwidth of 5 MHz is considered.

As SG traffic stresses the UL much more than the DL, there is no gain (but only extra cost) from the additional TX paths needed for MIMO in a dedicated utility optimized LTE network. To simplify the studies we assume no MIMO, i.e. 1TX-2RX in both cases, even though a CSP provided MBB network would typically deploy MIMO in order to boost user throughput.

To summarize, the following general system parameters will be assumed for the dedicated utility optimized LTE network:

LTE system parameters			
Duplex mode	FDD		
Channel BW	**5**	**MHz**	
Capacity scale factor	0.48		relative to 10 MHz
MIMO settings	1TX - 2RX		UL, DL

4.5.3 Frequency bands

When LTE is operated as dedicated network, the utility would need to have access to a licensed frequency band, either directly or on a leased basis. The licensed spectrum can be either a paired or unpaired band, as LTE supports both, the FDD and TDD duplex modes of operation.

Some countries, for example Canada have already designated spectrum @1.8 GHz to utilities for broadband communications, in other countries the regulators have still to make decisions. Utilities, notably in the US, might be interested in obtaining direct access to spectrum @700 MHz or by establishing partnerships with other stakeholders using LTE in the Public Safety and Critical Infrastructure space. In some countries, e.g. Australia, spectrum has been provided to utilities on a lease basis in order to facilitate wireless connections of meters.

Paired frequencies within the propagation and interference friendly licensed bands below 1 GHz are particularly attractive for LTE deployment. The Vattenfall / Finland service area is pre-dominantly of rural type with no major cities included. Providing universal coverage for such an area in bands (much) above 1 GHz is not economic. Also CSPs use bands < 1 GHz for rural MBB access. Furthermore, with pressure high on optimal radio link budgets (cell range), FDD is preferred over TDD.

Here we will use the 900 MHz[1] and close by 800 MHz[2] FDD bands in order to ease relative comparisons without the need to worry about the large impact from propagation related phenomena across different frequency bands. Bands < 1 GHz help also in so far as they connect to the available data from the numerous GSM900 automation use cases of today. While the 900 MHz band is not a typical band for public LTE, it is used for WCDMA900 in Finland and the close by 800 MHz is used on other countries for LTE, e.g. Germany, see [1].

[1] LTE Band 8

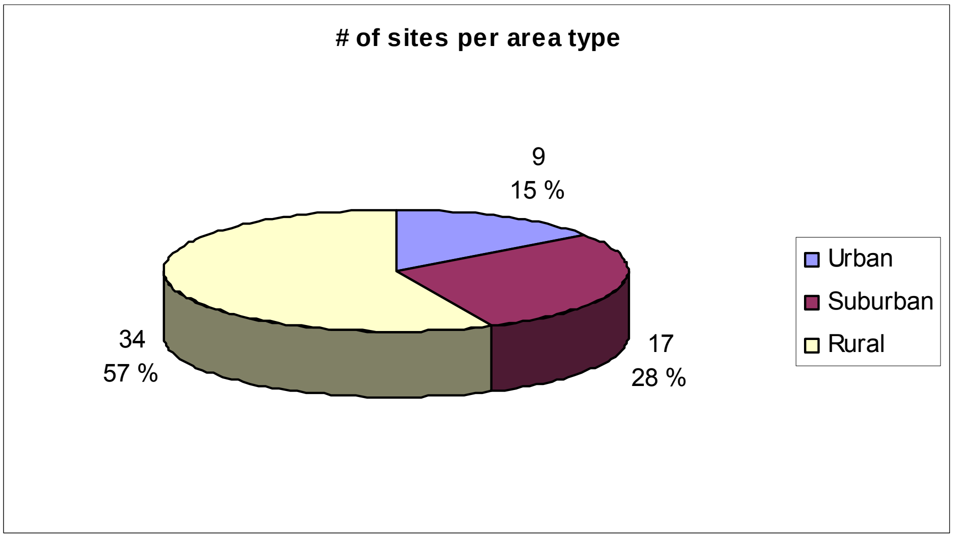
[2] LTE Band 20, not yet licensed in Finland

It must be remembered, that currently utilities don't have access to licensed broadband spectrum in Europe, in particular not to the 800 MHz band. The spectrum related situation in Europe is summarized in [3] from an EUTC perspective. An interesting topic for subsequent SGEM studies is evaluating the potential benefits and required amount of broadband spectrum licensed to utilities in Europe.

4.5.4 Radio link budgets

Following the utility scenario definition the next step in traffic dimensioning according to the methodology of Fig. 3-1 is estimating LTE cell sizes. Two cases for LTE network deployment are considered in the following radio link budget (RLB) analysis:

1. CSP provided 10 MHz LTE900 MBB network: the radio network is dimensioned for public MBB traffic and is compatible with an existing GSM900 site grid. SG M2M traffic, e.g. from AM locations will be picked up 'as is' without any impact on the radio network design (e.g. cell range).
2. Dedicated 5 MHz LTE800 network which is coverage optimized for the utility: here the field device RF site parameters (i.e. use of external antennas with meters) and cell design (range, RF site parameters) is optimized for the SG use case requirements only – this is done in order to minimize the number of required LTE sites. There is no existing 2G site grid and we can thus freely 'stretch' the sites in line with the SG traffic requirements in order to maximize radio coverage and keep investment costs low. With only M2M traffic present we don't need to worry about high (say 64 kbps) broadband bit rate user requirement at the cell edge and can instead design for lower data rates (say 16 kbps). The network can be designed solely for coverage and need not be made denser due to capacity. The cell edge design is set by providing coverage to meters and this will then also cover for the RTUs which have a more favorable link budget. With this approach, the respective low site counts for the VFV service area are as follows:



Background material on LTE radio link budgets can be found from [2].

4.5.4.1 CSP provided LTE MBB network

	UL center frequency [MHz]	897.5			Band 8
	Link budget Uplink	**Urban**	**Suburban**	**Rural**	
		LTE	**LTE**	**LTE**	
	Data rate [kbps]	**64**	**64**	**64**	
	Transmitter - RTU				
a	Max tx power [dBm]	23.0	23.0	23.0	
b	Tx antenna gain [dBi]	-2.0	-2.0	-2.0	USB stick with integrated antenna
c	Body loss [dB]	0.0	0.0	0.0	
d	EIRP [dBm]	**21.0**	**21.0**	**21.0**	=a+b-c
	Receiver - eNode B				
e	Node B noise figure [dB]	2.5	2.5	2.5	
f	Thermal noise [dBm]	-118.4	-118.4	-118.4	=k(Boltzmann)*T(290K)*B. Note 1
g	Receiver noise floor [dBm]	-115.9	-115.9	-115.9	=e+f
h	SINR [dB]	-0.35	-0.35	-0.35	10% BLER, Note 2
i	Receiver sensitivity [dBm]	-116.3	-116.3	-116.3	=g+h
j	Interference margin [dB]	3.0	3.0	3.0	Note 3
k	Cable loss [dB]	0.4	0.4	0.4	Note 4
l	Rx antenna gain [dBi]	15.5	16.5	17.0	
	Maximum path loss	**149.4**	**150.4**	**150.9**	=d-i-j-k+l

Note 1: B = noise bandwidth : LTE 2 PRB = 360 kHz
Note 2: 2-rx eNode B assumed, fast fading margin included
Note 3: low ... moderate load assumed
Note 4: Feederless site, tower top RF

	Link budget Downlink	**Urban**	**Suburban**	**Rural**	
		LTE	**LTE**	**LTE**	
	Data rate [kbps]	**1024**	**1024**	**1024**	
	Transmitter - eNode B				
a	Tx power [dBm]	46.0	46.0	46.0	
b	Tx antenna gain [dBi]	15.5	16.5	17.0	
c	Cable loss [dB]	0.4	0.4	0.4	
d	EIRP [dBm]	**61.1**	**62.1**	**62.6**	=a+b-c
	Receiver - RTU				
e	UE noise figure [dB]	7.0	7.0	7.0	
f	Thermal noise [dBm]	-104.5	-104.5	-104.5	=k (Boltzmann)*T(290K)*B, Note 1
g	Receiver noise floor [dBm]	-97.5	-97.5	-97.5	=e+f
h	SINR [dB]	-9.0	-9.0	-9.0	From simulations. Note 2
i	Receiver sensitivity [dBm]	-106.5	-106.5	-106.5	=g+h. Note 2
j	Interference margin [dB]	4.0	4.0	4.0	Note 3
k	Control channel overhead [%]	20.0 %	20.0 %	20.0 %	
l	Rx antenna gain [dBi]	-2.0	-2.0	-2.0	
m	Body loss [dB]	0.0	0.0	0.0	Body loss for voice terminal 3 dB
	Maximum path loss	**160.6**	**161.6**	**162.1**	=d-i-j-k+l-m

Note 1: B = noise bandwidth : LTE 50 PRB = 9 MHz
Note 2: 2-rx terminal assumed
Note 3: See Holma et al. p. 225

	Urban	Suburban	Rural	
eNode B antenna height [m]	30	30	50	
RTU antenna height [m]	1.5	1.5	1.5	
Location probability	95.0 %	95.0 %	95.0 %	high end NW
Slow fading standard deviation [dB]	12.0	10.0	9.0	
Indoor loss [dB]	17	13	13	high end NW
Slow fading margin [dB]	14.8	11.7	10.3	
Gain against shadowing [dB]	2.5	2.5	1.9	
Max path loss w/o clutter [dB]	149.4	150.4	150.9	
Max path loss with clutter [dB]	120.1	128.1	129.5	
Correction factor [dB]	0	-6	-17	
Okumura-Hata cell range for 3-sector sites				
			#NUM!	PL for R>20 km
Cell range [km]	**0.66**	**1.66**	**4.87**	
ISD [km]	1.00	2.49	7.31	
Cell area [km^2]	0.29	1.80	15.42	
Site area [km^2]	**0.86**	**5.39**	**46.25**	
Site count for utility area				
	Urban	Suburban	Rural	Total
Area [km^2]	94.1	1147.2	47758.7	49000
Required sites (for coverage)	**110**	**213**	**1033**	**1356**

4.5.4.2 Dedicated network optimized for utility

	UL center frequency [MHz]	847			Band 20
	Link budget Uplink	**Urban**	**Suburban**	**Rural**	
		LTE	**LTE**	**LTE**	
	Data rate [kbps]	**16**	**16**	**16**	
	Transmitter - RTU				
a	Max tx power [dBm]	23.0	23.0	23.0	
b	Tx antenna gain [dBi]	2.0	2.0	2.0	AMR with external antenna, incl. cable loss
c	Body loss [dB]	0.0	0.0	0.0	
d	EIRP [dBm]	**25.0**	**25.0**	**25.0**	=a+b-c
	Receiver - eNode B				
e	Node B noise figure [dB]	2.5	2.5	2.5	
f	Thermal noise [dBm]	-118.4	-118.4	-118.4	=k(Boltzmann)*T(290K)*B. Note 1
g	Receiver noise floor [dBm]	-115.9	-115.9	-115.9	=e+f
h	SINR [dB]	-6.2	-6.2	-6.2	HARQ gain, Note 2
i	Receiver sensitivity [dBm]	-122.1	-122.1	-122.1	=g+h
j	Interference margin [dB]	1.0	1.0	1.0	Note 3
k	Cable loss [dB]	0.4	0.4	0.4	Note 4
l	Rx antenna gain [dBi]	15.5	16.5	17.5	
	Maximum path loss	**161.2**	**162.2**	**163.2**	=d-i-j-k+l

Note 1: B = noise bandwidth : LTE 2 PRB = 360 kHz
Note 2: 2-rx eNode B assumed, fast fading margin included
Note 3: low load assumed
Note 4: Feederless site, tower top RF

	Link budget Downlink	**Urban**	**Suburban**	**Rural**	
		LTE	**LTE**	**LTE**	
	Data rate [kbps]	**1024**	**1024**	**1024**	
	Transmitter - eNode B				
a	Tx power [dBm]	46.0	46.0	46.0	
b	Tx antenna gain [dBi]	15.5	16.5	17.5	
c	Cable loss [dB]	0.4	0.4	0.4	
d	EIRP [dBm]	**61.1**	**62.1**	**63.1**	=a+b-c
	Receiver - RTU				
e	UE noise figure [dB]	7.0	7.0	7.0	
f	Thermal noise [dBm]	-104.5	-104.5	-104.5	=k (Boltzmann)*T(290K)*B, Note 1
g	Receiver noise floor [dBm]	-97.5	-97.5	-97.5	=e+f
h	SINR [dB]	-9.0	-9.0	-9.0	From simulations. Note 2
i	Receiver sensitivity [dBm]	-106.5	-106.5	-106.5	=g+h. Note 2
j	Interference margin [dB]	4.0	4.0	4.0	Note 3
k	Control channel overhead [%]	20.0 %	20.0 %	20.0 %	
l	Rx antenna gain [dBi]	2.0	2.0	2.0	
m	Body loss [dB]	0.0	0.0	0.0	Body loss for voice terminal 3 dB
	Maximum path loss	**164.6**	**165.6**	**166.6**	=d-i-j-k+l-m

Note 1: B = noise bandwidth : LTE 50 PRB = 9 MHz
Note 2: 2-rx terminal assumed
Note 3: See Holma et al. p. 225

	Urban	Suburban	Rural	
eNode B antenna height [m]	30	30	80	
RTU antenna height [m]	1.5	1.5	1.5	
Location probability	90.0 %	90.0 %	90.0 %	
Slow fading standard deviation [dB]	12.0	10.0	9.0	
Indoor loss [dB]	15	10	8	IPL to meter location
Slow fading margin [dB]	10.1	7.8	6.7	
Gain against shadowing [dB]	2.5	2.5	1.9	
Max path loss w/o clutter [dB]	161.2	162.2	163.2	
Max path loss with clutter [dB]	138.6	146.9	150.5	
Correction factor [dB]	0	-6	-17	
Okumura-Hata cell range for 3-sector sites				
			150.5	PL for R>20 km
Cell range [km]	**2.33**	**5.93**	**27.00**	
ISD [km]	3.49	8.89	40.50	
Cell area [km^2]	3.52	22.83	473.50	
Site area [km^2]	**10.55**	**68.50**	**1420.50**	
Site count for utility area				
	Urban	Suburban	Rural	Total
Area [km^2]	94.1	1147.2	47758.7	49000
Required sites (for coverage)	**9**	**17**	**34**	**60**

4.5.4.3 Observations and comparison

First, it's clear that the UL is the limiting link, mainly due to limited TX power and EIRP of the mobile, respectively field device (meter).

Secondly, the number of required sites for the coverage optimized dedicated LTE800 network is *by a factor of 22 lower* compared to the CSP provided LTE MBB network – 60 sites instead of 1356 for the VFV service area scenario. This significant difference is due to the following underlying assumptions in the RF parameters:

- 2 dBi external antenna gain for the meter compared to low mobile device antenna gain ➔ 4 dB difference. For fixed installed meters there are no EIRP limits nor do mobile device SAR limits apply facilitating the use of external antennas. However, there is a cost penalty equipping meters (i.e. those at the cell edge) with external antennas which must be weighted against the cost of additional BS sites.
- UL cell edge bit rate of only 16 kbps @ 4-TX HARQ gain vs. 64 kbps @ 10% BLER ➔ 5.85 dB lower C/I for the coverage optimized dedicated LTE800 network. This lower bit rate is sufficient for M2M connections. The increased latency and air-interface utilization due to the additional HARQ re-transmissions are acceptable for the considered UCs. Hence, latency and capacity have been traded for coverage in order to minimize the site count.
- Less load in the dedicated LTE network with M2M traffic only ➔ 2 dB lower interference margin.
- Sites optimized for coverage only ➔ 80 m masts ➔ better propagation.

- 90% vs. 95% location probability ➔ 3.6 dB less fading margin. Meters don't move and in case of poor coverage, the reception can be permanently improved, e.g. using 5 dBi external antennas or installing the antennas outdoors (at a cost penalty).
- Lower building penetration losses for meter locations than for high quality CSP network aiming at universal coverage, e.g. with row houses meters are often placed outside the house in accessible cabinets with wooden doors ➔ estimated 2 ... 5 dB advantage.
- All in all, these differences accumulate to ~21 dB higher allowed maximum path loss (with clutter) for the coverage optimized dedicated LTE utility network.

The RF design and site counts of these two LTE example networks represent the extremes: high quality CSP provided MBB networks in Nordic countries tend to operate with comparable high site densities. On the other hand, the parameters related to the coverage optimization of the dedicated LTE utility network are set on the aggressive side and the resulting cell sizes are likely at the upper limits of what can be achieved in practice. There are also some uncertainties on realistic parameter values for a variety of environments, e.g. those related to building penetration losses for meter locations.

4.5.5 Meters and RTUs per cell

Field device spatial densities are never truly uniform in practice; there is an unavoidable variance (peak vs. average) of the field device population seen by a cell. Calculation of cell peak loading requires estimates of the *peak* amount of field devices within a cell. This peak amount is obtained from the average value by scaling with suitable cell peak-to-average ratios (PAR) as follows.

The *average* amount of meters and RTUs per cell can be obtained from the information related to the device densities within the utility area (Section 4.1, Table 4.1-1) and LTE cell ranges (Section 4.5.4). The parameter *Area peak to average # of devices per cell* models mid-scale peak-to-average variations in the amount of field devices within a cell.

Parameters			
Location percentile	0.95		
	Urban	Suburban	Rural
Area peak to average # of devices per cell	3	3	3

This will be overlaid with a spatial Poisson process (parameter *Location percentile*) to capture small-scale random variations and to ensure that each cell sees at least one of the devices, in particular those with potential of generating significant traffic like primary substation GWs. This will happen in accordance with the inverse Poisson CDF except for very low spatial densities as can be seen from the following tables.

This results in the following values for meters and RTUs per cell:

4.5.5.1 CSP provided LTE MBB network

Average # of devices per cell			
	Urban	Suburban	Rural
AM	158.5	131.7	82.9
Disconnector	0.061	0.469	0.436
GW_SS	0.009	0.014	0.034
Recloser	0.000	0.047	0.032
Total	**158.6**	**132.2**	**83.4**

Peak # of devices per cell			
	Urban	Suburban	Rural
AM	512	428	275
Disconnector	1	4	3
GW_SS	0	0	1
Recloser	0	1	1
Total	**513**	**433**	**280**

PAR of devices per cell			
	Urban	Suburban	Rural
AM	3.23	3.25	3.32
Disconnector	16.41	8.52	6.88
GW_SS	0.00	0.00	29.79
Recloser	1.00	21.30	30.98

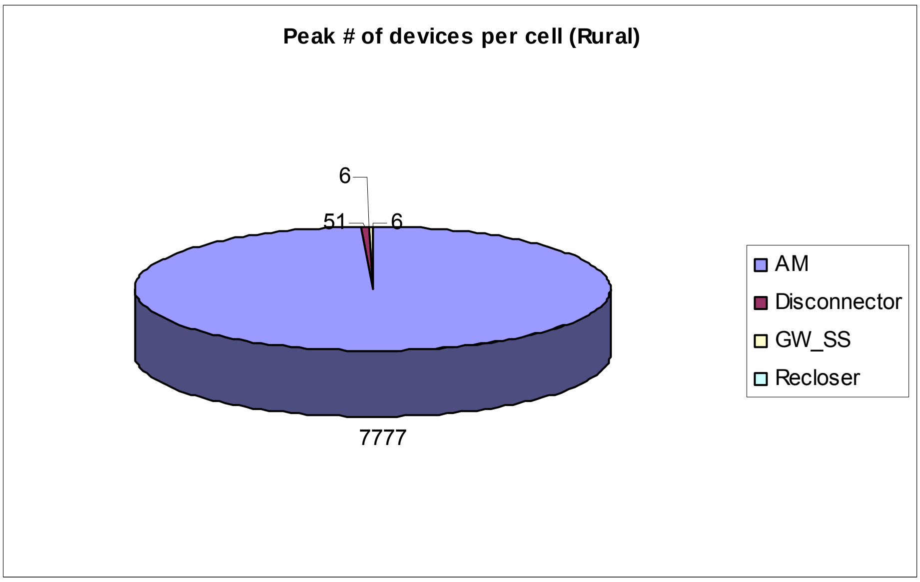
4.5.5.2 Dedicated network optimized for utility

Average # of devices per cell			
	Urban	Suburban	Rural
AM	1943.5	1674.8	2547.3
Disconnector	0.747	5.971	13.384
GW_SS	0.112	0.179	1.031
Recloser	0.000	0.597	0.991
Total	**1944.3**	**1681.6**	**2562.7**

Peak # of devices per cell			
	Urban	Suburban	Rural
AM	5953	5140	7777
Disconnector	5	25	51
GW_SS	1	2	6
Recloser	0	4	6
Total	**5959**	**5171**	**7840**

PAR of devices per cell			
	Urban	Suburban	Rural
AM	3.06	3.07	3.05
Disconnector	6.69	4.19	3.81
GW_SS	8.92	11.17	5.82
Recloser	1.00	6.70	6.05

The limiting case from a cell peak load perspective is repeated here also as a chart:



4.5.5.3 Observations and comparison

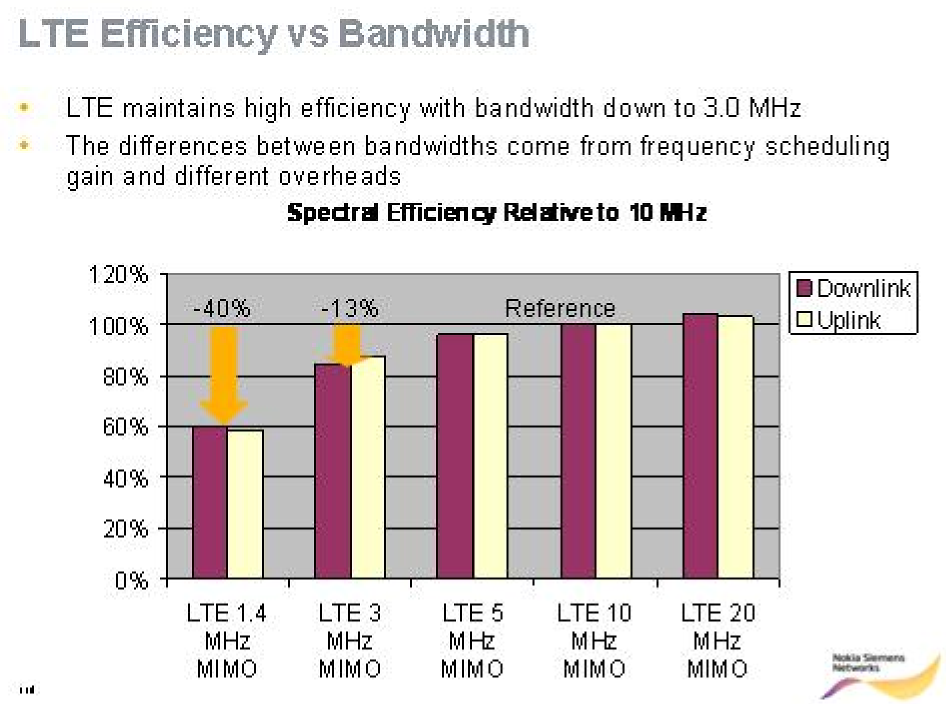
There is significant variation in number of attached meters/RTUs per cell depending on the LTE site densities. For example, rural cells of the coverage optimized dedicated LTE utility network are able to pick up ~30x the amount of meters due to their correspondingly larger coverage area. These cells are able to concentrate the generally sparsely distributed SG field devices and their traffic. This also means that they are potentially more vulnerable to overload in presence of SG traffic with very large peak-to-average characteristics (e.g. during power outages / storms).

4.5.6 LTE spectral efficiency (SE), air interface capacity

Yet another step in traffic dimensioning according to the methodology of Fig. 3-1 is to relate the carried SG traffic to the actual LTE cell throughput (i.e. capacity) and to compute the resulting M2M session densities, e.g. for quasi-simultaneous meter reads, alarms etc. For this assumptions on LTE spectral efficiency need to be made.

Background material on the factors impacting LTE spectral efficiency can be found in [2]. In particular, the used channel bandwidth, MIMO modes (here: no MIMO, instead 1TX, 2-RX is assumed) and base station inter-site distance (obtained from RLB) are relevant.

The SE relative to 10 MHz channel BW can be obtained from the following chart:



Taking also the actual channel bandwidth into account leads to the following capacity scale factors relative to 10 MHz:

Capacity scale factor relative to 10 MHz			
Channel BW [MHz]	Capacity scale factor		
1.4	0.084		
3	0.261		
5	0.48		
10	1		

The following tables provide estimates of the 10 MHz LTE cell specific air interface capacity (at MAC layer) which were interpolated from system simulations for given load points. These figures are relatively conservative estimates for SE, as possible gains from additional LTE capacity features (MIMO, enhanced scheduling options, etc) are not included. Overheads due to control channels are already deducted.

Also the system total air interface capacity (i.e. sum across all cells), for the given channel bandwidth (10 MHz for CSP LTE, 5 MHz for DNW LTE) is shown in separate tables.

4.5.6.1 CSP provided LTE MBB network

CSP LTE cell SE, 10 MHz				
	Urban	Suburban	Rural	Total
DL - Average SE (homogeneous cell loading)				
25 % load	3845.4	3095.7	2804.8	kbps
50 % load	6713.0	6002.1	5609.6	kbps
70 % load	8763.7	8323.5	7853.4	kbps
DL - Peak SE (heterogeneous cell loading, target cell 100%)				
25 % load	15381.6	12382.8	11219.1	kbps
50 % load	13426.1	12004.2	11219.1	kbps
70 % load	12519.5	11890.6	11219.1	kbps
UL - Average SE (homogeneous cell loading)				
25 % load	2234.1	1563.6	1337.9	kbps
50 % load	3900.1	3031.5	2675.8	kbps
70 % load	5091.5	4204.0	3746.1	kbps
UL - Peak SE (heterogeneous cell loading, target cell 100%)				
25 % load	8936.4	6254.3	5351.6	kbps
50 % load	7800.2	6063.1	5351.6	kbps
70 % load	7273.6	6005.8	5351.6	kbps

EPS Capacity summary					
System total air interface average capacity @ MAC @ 70% load					
	Urban	Suburban	Rural	Total	
# of sites (eNB)	110	213	1033	**1356**	
# of cells	330	639	3099	**4068**	
DL [Gbps]	2.89	5.32	24.34	**32.55**	Gbps
DL [GB/h]	1301.41	2393.41	10951.92	**14646.73**	GB/h
DL [TB/month]	937.01	1723.25	7885.38	**10545.65**	TB/month
UL [Gbps]	1.68	2.69	11.61	**15.98**	Gbps
UL [GB/h]	756.09	1208.87	5224.15	**7189.11**	GB/h
UL [TB/month]	544.38	870.39	3761.39	**5176.16**	TB/month
Cell air interface peak capacity @ MAC @ 25 % surrounding cell load					
	Urban	Suburban	Rural		
DL [kbps]	15381.6	12382.8	11219.1	kbps	
UL [kbps]	8936.4	6254.3	5351.6	kbps	

4.5.6.2 Dedicated network optimized for utility

DNW LTE cell SE, 10 MHz				
	Urban	Suburban	Rural	Total
DL - Average SE (homogeneous cell loading)				
25 % load	3087.6	2810.1	2195.9	kbps
50 % load	5991.3	5616.9	4574.8	kbps
70 % load	8310.6	7862.2	6404.7	kbps
DL - Peak SE (heterogeneous cell loading, target cell 100%)				
25 % load	12350.3	11240.5	9149.6	kbps
50 % load	11982.6	11233.8	9149.6	kbps
70 % load	11872.3	11231.7	9149.6	kbps
UL - Average SE (homogeneous cell loading)				
25 % load	1557.3	1342.0	698.6	kbps
50 % load	3021.8	2682.4	1455.4	kbps
70 % load	4191.5	3754.7	2037.6	kbps
UL - Peak SE (heterogeneous cell loading, target cell 100%)				
25 % load	6229.0	5368.1	2910.8	kbps
50 % load	6043.5	5364.9	2910.8	kbps
70 % load	5987.9	5363.9	2910.8	kbps

EPS Capacity summary					
System total air interface average capacity @ MAC @ 70% load					
	Urban	Suburban	Rural	Total	
# of sites (eNB)	9	17	34	**60**	
# of cells	27	51	102	**180**	
DL [Gbps]	0.11	0.19	0.31	**0.61**	Gbps
DL [GB/h]	48.47	86.61	141.11	**276.19**	GB/h
DL [TB/month]	34.90	62.36	101.60	**198.85**	TB/month
UL [Gbps]	0.05	0.09	0.10	**0.25**	Gbps
UL [GB/h]	24.45	41.36	44.89	**110.70**	GB/h
UL [TB/month]	17.60	29.78	32.32	**79.70**	TB/month
Cell air interface peak capacity @ MAC @ 25 % surrounding cell load					
	Urban	Suburban	Rural		
DL [kbps]	5928.2	5395.4	4391.8	kbps	
UL [kbps]	2989.9	2576.7	1397.2	kbps	

4.5.6.3 Observations and comparison

DL capacity is by a factor of 2 … 2.5 larger than UL capacity. With DL MIMO, this imbalance could increase by yet another ~20%. On the other hand, a much larger portion of the SG traffic is expected on the UL (field device ➔ SCADA/DMS).

The so called “coverage vs. capacity trade-off” can also be observed when comparing the tables for 10 MHz LTE. Due to large cells sizes and lower fading and interference margins the coverage optimized dedicated LTE utility network operates close to the “thermal noise limit”. This means that the field devices operate relatively more often at their TX power limits and cannot use spectrally more efficient modulation and coding schemes. For example, only 54% of the UL cell capacity of the CSP operated LTE network is reached (assuming 10 MHz in both cases).

These figures also show that the CSP operated much denser LTE network possess ~65x the aggregate UL air interface capacity for the same area, mainly due to the much larger number of sites and double bandwidth (10 MHz for CSP LTE, 5 MHz for DNW LTE).

4.5.7 Observations and Suggestions

Compared to the CSP operated dense LTE network, the stretched rural cells of the coverage optimized dedicated LTE utility network concentrate SG field devices and their traffic by a factor of ~30. At the same time their air interface capacity is lower by a factor of 1/(0.54*0.48) = 3.85 (on the UL). This is a combined relative disadvantage for the rural utility DNW cell of factor 115.5 in dealing with SG traffic relative to a CSP cell. This means that the coverage optimized dedicated LTE utility network is potentially more vulnerable to overload in presence of SG traffic with very large peak-to-average characteristics (e.g. during power outages / storms, aggressive meter reads).

Therefore it is proposed to start the LTE network dimensioning studies with this worst case first.

4.6 (Void)

4.7 Satellite Access (contributed by Elektrobit)

Today, terrestrial cellular systems provide coverage for most of the populated areas. Compared to satellite solutions, terrestrial systems provide superior capacity and are more economical, easy to build and maintain, and are expandable, while the satellites are expensive to build and operate and they provide quite limited capacity. Thus, the satellite communications market is much smaller and does not grow as fast as the terrestrial communications. However, the satellite systems have one major advantage; global coverage. Distant and unpopulated areas that are not covered by terrestrial cellular systems or even land line telephone can be reached via satellites. Many terrestrial operators use the satellite as backhaul from very remote areas as the most cost effective means of transport. Table 4.7.1 shows the frequency allocations for different satellite communication services.

Table 4.7.1: Typical frequency band allocations for FSS, MSS and BSS.

Radio communications services	Frequency bands for uplink/downlink	Usual terminology
Fixed satellite services (FSS)	6/4GHz 8/7GHz 14/12-11 GHz 30/20 GHz 50/40GHz	C band X band Ku band Ka band V band
Mobile satellite services (MSS)	1.6/1.5 GHz 2/2.2 GHz 30/20GHz	L band S band Ka band
Broadcasting satellite services (BSS)	2/2.2 GHz 12 GHz 2.6/2.5GHz	S band Ku band S band

Many of the current two-way satellite communications systems are using GSM/GPRS based air interface technology. As an example, Thuraya a service provider of voice, data, maritime, rural telephony, and fleet management over 140 countries, uses GMR-1 air interface while ASIA Cellular Satellite Network (ACeS) uses GMR-2 interface. The evolution of the GMR satellite air interface is depicted in Figure 4.7.1 below.

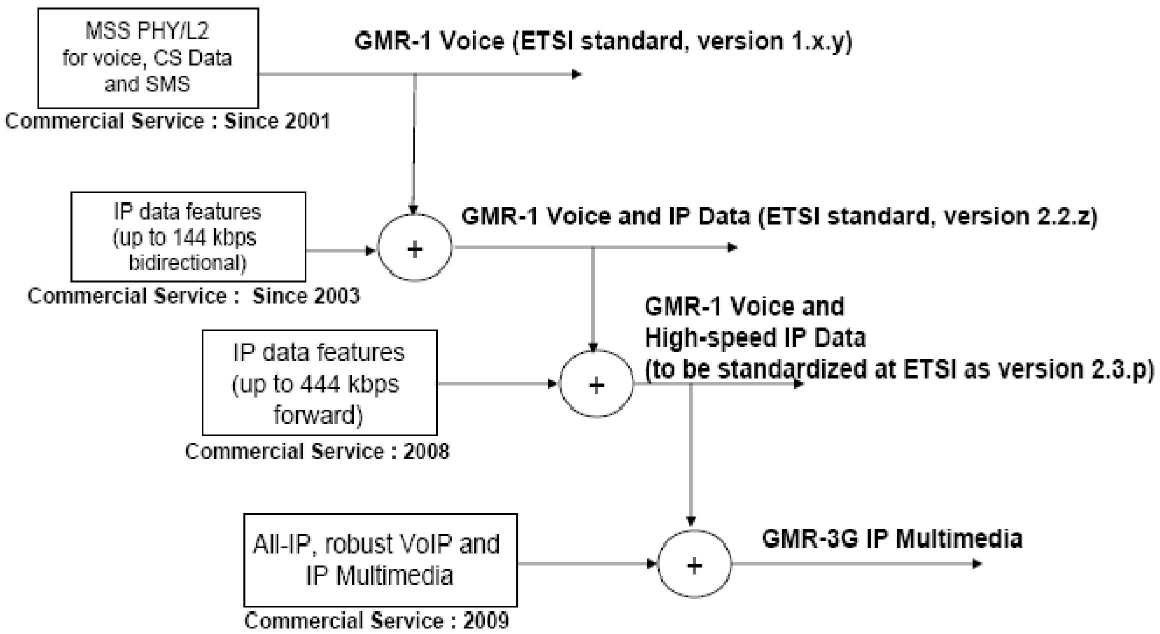


Figure 4.7.1: Evolution from GMR-1 to GMR-1 3G.

GMR-1 3G uses TDMA/FDMA scheme, which has especially been developed for satellite link applications. Despite the term “3G”, GMR-1 3G is not based on any terrestrial 3G system, but it represents the third generation of satellite communications systems. GMR-1 3G terminal uses separate dedicated transceivers to handle the terrestrial and satellite connections.

While the more advanced systems are coming in the near future, the well established service providers such as Inmarsat have also developed their own systems supporting both voice and data services. Inmarsat’s BGAN (Broadband Global Area Network) service is one of the first mobile communication service that was able to deliver both voice and broadband data simultaneously through a single portable device. BGAN offers broadband connectivity for single and multiple users, who wish to set up, for example, a mobile office anywhere in the world.

More advanced systems based on terrestrial communications technologies such as S-UMTS, S-WiMAX, and S-LTE have been considered and they may be deployed within a few years. S-UMTS and other terrestrial based systems provide the advantage of allowing the same transceiver to be used for both satellite and terrestrial connection, which simplifies the terminal and reduces cost. In addition to more compact terminal design, S-UMTS, S-WiMAX, and other terrestrial based future satellite such as S-LTE systems provide also other advantages. For example, the satellite and terrestrial networks can share the same frequency bands in hybrid mode, thus enhancing the spectral efficiency. In addition to improved spectral efficiency, combining the terrestrial and satellite service in the same hybrid domain offers interesting opportunities to apply the cognitive radio concepts. The shared spectrum can be part of a band allocated to satellite operators or to mobile operators.

4.7.1 Satellite orbits

At geosynchronous orbits (GEOs) the satellites roughly hover over the same meridian being only half a sidereal day above each hemisphere. The distance to the satellites when they appear above Europe is approximately 36 000 km. Geostationary orbit is above the equator and distance to the satellites is approximately 37 000 km in Finland. It is a special case of geosynchronous (GEO) orbits.

Medium-Earth orbits (MEOs) are at the altitudes between 1 700 – 23 786 km and the corresponding cycle times are ranging from approximately two hours to less than a sidereal day. They are commonly used by the navigation systems such as GPS, Glonass and Galileo, in which the satellite altitudes are close to 20 000 km. A MEO can be designed in such way that the same areas on Earth will be crossed two times a day. For a communication link usage, the MEOs are a compromise between GEO and Low-Earth orbits (LEOs), though perhaps not the best one: they do not possess any fixed position in relation to Earth, but the orbit altitude is still relatively high.

Elliptical orbits, a.k.a. Molniya orbits, which can visit the heights below 500 km in their operational position around the perigee, but which still can have the cycle time of the sidereal day – or half of it. They can be very efficient especially when communications in the higher latitudes are the matter concern.

At Low-Earth orbits (LEO), the satellites are e.g. at the heights of 400 – 1700 km and the cycle times can be e.g. 1/12, 1/14, or 1/16 of the sidereal day in order to make their orbiting synchronous with the rotation of Earth. The low orbits make them advantageous in terms of link budget, but there have to be several satellites in order to obtain continuous transmission. Examples of LEO satellite systems include Iridium and Globalstar.

The GEO satellites are good at broadcasting services, where same signals are to be received by multiple terrestrial users over large areas. Contrary to the broadcasting the lower orbits offer a lot of benefits in two-way mission. Accessing a GEO satellite is challenging for a handheld device with a low gain antenna, although it works in the open air provided there is a sufficient amount power available. Link budgets and sensitivity requirements are rather different for the GEO satellites in comparison with the LEO satellites. The drawback for using LEO system is that it needs numerous satellites to meet the coverage requirement.

4.7.2 Frequency bands

An overview of the frequency bands is shown in Table 4.7.1. This section presents a more detailed description of the existing frequency allocations in satellite communications.

The band 1 452 - 1 492 MHz (downlink) is allocated on a co-primary basis with the broadcasting satellite service to the terrestrial fixed, mobile and broadcasting services. The use of this band by the broadcasting-satellite and terrestrial broadcasting services is limited to digital audio broadcasting.

European Conference of Postal and Telecommunications administrations (CEPT) has decided that the frequency bands 1 518 - 1 525 MHz and 1 670 - 1 675 MHz are designated to the mobile satellite service (MSS). Explicitly is mentioned the possibility for MSS systems in these bands to incorporate a complementary ground component (CGC).

The bands 1 626.5 - 1 660.5 MHz and 1 668 - 1 675 MHz (uplink) and correspondingly 1 518 - 1 559 MHz (downlink) are allocated almost worldwide to the mobile satellite service (MSS) and are mainly used by MSS operators using geostationary satellites to provide two-way mobile satellite communications. The band 1 610 - 1 626.5 MHz (up and downlink) is allocated worldwide to MSS and is used by MSS operators using LEO satellites.

The bands 1 980 - 2 010 MHz and 2 170 - 2 200 MHz are allocated worldwide to the fixed, mobile and mobile satellite (space-to-Earth) services on a co-primary basis. It means that, from a regulatory point of view, these three services enjoy the same status. The bands can basically be used by both GEO and LEO satellites.

The bands 2 500 - 2 520 MHz (downlink) and 2 670 - 2 690 MHz (uplink) are allocated world wide to MSS and are shared with terrestrial (fixed and mobile) services. There the geostationary satellites and non-geostationary systems are on an equal footing with regards to spectrum access.

Slightly over 3 GHz is a band for FSS satellites, although, they operate mainly at the C band, from 3.7 to 4.2 GHz (downlink) and from 5.925 GHz to 6.425 GHz (uplink). These bands are better under adverse weather conditions than the higher frequencies, which are also used for FSS, e.g., the Ku band (11.45 - 11.7 GHz and 12.5 - 12.75 GHz in Europe for downlink and 14 - 14.5 GHz for uplink). The bands 17.3 GHz to 20.2 GHz (downlink) and 27.5 GHz to 30 GHz (uplink) are allocated by ECC decision to fixed satellite services (FSS) and fixed (terrestrial) services (FS). In addition, sub-bands for uncoordinated FSS transmission have also been allocated.

4.7.3 Satellite channel models

The types of the satellite services can be classified in three types:

- Broadcast Satellite Service (BSS) using GEO/LEO orbit and fixed/mobile terminals at 2 to 12 GHz.
- Mobile Satellite Service (MSS) using GEO/LEO orbit and mobile terminals at 1.5 to 20 GHz.
- Fixed Satellite Services (FSS) using geostationary orbit and fixed terminals at frequency bands 4 to 50 GHz.

There are topologically two different ways of how the connection from satellite to Earth is created:

- Direct connection satellite – user equipment.
- Connection via an Earth relay station or comparable.

Satellite-Earth channel models depend on the satellite distance, the allocated frequency band (as well as bandwidth), elevation angles and the radio environments at Earth surface. The higher frequency bands at BSS and MSS are applied in satellite-to-terrestrial gateways while the satellite-to-terrestrial links employ L- or S-band. Signal propagation between geostationary or geosynchronous orbit and Earth encounters considerably higher path-loss than the link between LEO orbit and Earth surface. On the other hand, LEO orbit satellite connections suffer from much higher Doppler effect. It is also noted that carrier frequencies have a significant impact on the path-loss.

In general, the following specific propagation effects should be considered:

- For L- and S-band
  - Attenuation (shadow fading) due to trees in static and mobile cases.
  - Multi path fading due to roadside trees, at canyon and hilly, urban, rural etc. environments at L- and S-band.
  - Earth-satellite propagation effects inside buildings, building penetration, and building blocking at L- and S-band.
- For Ku, Ka and V band
  - Attenuation by the precipitations in the troposphere.

Earth-satellite link in most cases can be regarded as line-of-sight, and therefore, the popular channel model is Ricean with specific Rice factor. However, in the shadowing and blocking cases, the channel can be also regarded as Rayleigh. In wideband communications, e.g. DVB-SH, the channel bandwidth may be in the range of 8-10 MHz, which requires wideband channel modeling. This can be designed by tapped-delay-line (TDL) channel models such as the 3GPP Spatial Channel Model (SCM). TDL channel models are usually applied when simulating terrestrial links in urban/suburban/rural environments. For Earth-satellite wideband communications TDL models are not yet widely used.

For FSS and the service between the terrestrial gateway and satellite in MSS and BSS, higher than C band is applied, and the link can be characterized as line-of-sight. In addition, the antennas are more directive so that multipath fading and shadowing can be neglected. However, for L- and S-band applied in MSS and BSS (e.g. DVB-SH), we should take into account the shadow fading, i.e. blocking effect for example by trees and buildings in addition to multipath fading. At frequencies below 6 GHz the attenuation caused by rain and other precipitations can generally be neglected.

Considering the frequency band below 6 GHz, it can be stated that narrowband satellite radio channel modeling is applicable only for systems with signal bandwidth well below 5 MHz. ITU recommendations P.681 presents a narrowband 3-state Markov model with tabulated state statistics **Error! Reference source not found.**. This model has been the basis for a narrowband 2-state semi-Markov model by Bråten [23]. In a recent development, Pérez-Fontán has developed a 2-state Markov model which includes satellite elevation and street orientation effects as well as the building density [24]. As mentioned before a tapped delay line wideband model such as the SCM channel model can be employed for 5-20 MHz channel bandwidths.

4.7.4 Channel bandwidth, MIMO

In satellite systems, it is typical that the propagation path loss from the transmitter to the receiver is high. This leads to limited SNR at the receiver if reasonable TX power is assumed with realistic antennas. One way to mitigate this problem is to reduce the signal bandwidth in order to reduce the noise power in the receiver. This reduces of course the system data throughput.

In principle LTE offers an attractive choice for a hybrid terrestrial-satellite wireless communication system. The wide variety of available bandwidths of LTE (1.4 MHz- 20 MHz) includes rather narrowband options of 1.4 MHz and 3.0 MHz which may be feasible for some satellite applications. On the other hand, LTE system can allocate radio resources on a single Resource Block (RB) basis, which covers only 180 kHz frequency band. This makes it possible for a small terminal device to get a connection to the satellite with limited TX power. It is an important feature for Smart Grid (SG) application, which requires only a small data rate per field device.

One important issue for satellite coverage is the large number of mobile data devices which need to be connected to the base station simultaneously. In terrestrial LTE network, e.g. 1000 users could be connected to a 3-sector base station simultaneously, which is already demanding from the MAC layer processing viewpoint. In satellite cell, this number can be dramatically larger. This problem remains challenging even if the users are allocated to multiple narrow LTE bands of 1.4 MHz.

Multiple-Input, Multiple-Output (MIMO) technique is able to increase peak data rates and spectral efficiency as long as radio channel conditions are favorable. As mentioned before, the MIMO approach is currently specified in LTE only for downlink. Even if in future it may be applied also in uplink, it is not very attractive for satellite based SG application mainly due to the following reasons:

- MIMO requires parallel TX chains which complicates the transceiver.
- MIMO requires high SNR at the receiver.
- MIMO requires low-correlated antennas which may be a challenge in line-of-sight type of satellite communications.
- MIMO increases mainly peak data rates/ spectral efficiency.

Table 4.7.2 below summarizes the main system parameters which are assumed in the following radio link calculations. Here we assumed the 800 MHz frequency so that a hybrid terrestrial/satellite network could be designed with as few base stations as possible. In case that a hybrid satellite-terrestrial coverage is built based on an LTE technology, the most interesting frequency bands are those specified by ITU for IMT systems. Interesting bands include the following: 450 MHz, 700-800 MHz, 1600MHz (satellite only), 2200 MHz (satellite only), 2500-2700 MHz, and 3400-3600 MHz. Actually, the 450-470 MHz band would be even more attractive for cost-efficient coverage building. The smallest bandwidth of 1.4 MHz was chosen due to the fact that the required data rates are rather modest.

Table 4.7.2: LTE system parameters for satellite coverage.

LTE system parameters	
Carrier frequency	800 MHz
Duplex mode	FDD
Channel bandwidth	1.4 MHz
MIMO setting	1 TX/ 2 RX

4.7.5 Radio link budgets, antennas and cabling

Radio link budgets

In the following, the path loss for both the GEO and LEO systems are evaluated for these frequency bands. Typical LEO satellite system may have satellite-terminal distance of 800 - 1500 km (e.g. Iridium and Globalstar). The corresponding *free space propagation path loss* values are shown in Table 4.7.3 below.

Table 4.7.3: Free space propagation path loss for LEO satellite.

Path loss for LEO satellite		
	Dist=800 km	***Dist=1500 km***
Carrier frequency [MHz]	Path loss [dB]	Path loss [dB]
450	143,5	149
800	148,5	154
1600	154,5	160
2200	157,5	163
2600	159	164
3500	161	166,5

Depending on the allocated frequency spectrum the propagation path loss values fall into a similar range as for the terrestrial systems (see 4.6.3.2). Thus, in principle, it is feasible to built LTE coverage from a LEO satellite system. As discussed above, we assume a hybrid 1.4 MHz LTE800 network using both terrestrial and satellite based eNodeB's. This network could serve various applications including smart grid (SG) use cases. The SG system requirements are taken into account in the following. For example, the field device applies external antennas to minimize TX power requirements. The system is designed mainly for wide area coverage with low data rates.

The link budget for a LEO satellite at 800 km distance is calculated in the following (see also **Error! Reference source not found.** for reference). In this calculation, we assumed that in the downlink the satellite TX power is 4W for 1.4MHz band while its antenna gain is 20 dBi (for reference, the maximum antenna gain of the Iridium satellite is 24 dB). It was assumed that low data rate with QPSK-1/2 modulation and coding scheme is applied which gives about 0.7 Mbit/s overall data throughput. Compared to the free space loss the link budget leaves almost 10 dB margin for shadowing/non-favorable satellite orientation. On favorable conditions higher MCS can be applied for enhanced system throughput.

Satellite Link Budget: Downlink		
Satellite distance	800	km
Carrier frequency	800	MHz
Noise bandwidth, B	1400000	Hz
Free space path loss	148,5	dB
Boltzmann constant k	1,38E-23	J/K
NF	7	dB
T	290	K
k* T* B	-112,5	dBm
Receiver noise floor	-105,5	dBm
Required SNR	3	dB
Receiver sensitivity	-102,5	dBm
TX EIRP	56	dBm
RX antenna gain	2	dBi
Interference margin	3	dB
Maximum path loss	157,5	dBm

The link budget of the uplink is calculated for a single resource block (180 kHz bandwidth) to count for the low TX power of the terminal. Thus the maximum data rate is 120 kbit/s. TX power of 250 mW with antenna gain of 2 dBi was employed in the link budget.

Satellite Link Budget: Uplink		
Satellite distance	800	km
Carrier frequency	800	MHz
Noise bandwidth, B	180000	Hz
Free space path loss	148,5	dB
Boltzmann constant k	1,38E-23	J/K
T_system	827	K
k* T* B	-116,9	dBm
Receiver noise floor	-116,9	dBm
Required SNR	3	dB
Receiver sensitivity	-113,9	dBm
TX EIRP	26	dBm
RX antenna gain	20	dBi
Interference margin	3	dB
Maximum path loss	156,9	dBm

In case of geostationary/geosynchronous MSS satellite systems, the distance between the satellite and the terminal (in Finland) is roughly 37000 km. This scenario leads to the following path losses at different carrier frequencies (Table 4.7.4).

Table 4.7.4: Path loss for GEO satellite.

Path loss for GEO satellite (d=37000 km)	
Carrier frequency [MHz]	Path loss [dB]
450	177
800	182
1600	188
2200	191
2600	192
3500	195

Considering the GEO satellite system, we assume again a hybrid 1.4 MHz LTE800 network using both terrestrial and satellite based eNodeB's. The system is optimized for the SG use case requirements similarly as with the LEO case.

The link budget for a GEO satellite at 37000 km distance is calculated assuming QPSK-1/2 modulation and coding scheme (0.7 Mbit/s data throughput for the entire system). In this case it is assumed that the fixed SG terminal antennas have fixed orientation towards the GEO satellite so that a directive external antenna can be used. Antenna gain of 8 dBi is assumed. Due to the Line-of-Sight conditions it is expected that a significant margin for shadowing is not required. The link budget can be further enhanced by increasing the TX power levels or by employing a lower modulation and coding scheme, e.g. QPSK-1/3 or QPSK-1/5. In downlink, 8W TX power per 1.4 MHz was applied with 36 dBi antenna gain.

Satellite Link Budget: Downlink		
Earth radius	6371	km
Satellite height	35786	km
Satellite distance	37221	km
Carrier frequency	800	MHz
Noise bandwidth, B	1400000	Hz
Free space path loss	182	dB
Boltzmann constant k	1,38E-23	J/K
NF	7	dB
T	290	K
k* T* B	-112,5	dBm
Receiver noise floor	-105,5	dBm
Required SNR	3	dB
Receiver sensitivity	-102,5	dBm
TX EIRP	75	dBm
RX antenna gain	8	dBi
Interference margin	3	dB
Maximum path loss	182,5	dBm

In uplink, the SG terminal TX power of 500 mW was assumed with 8 dBi external antenna.

Satellite Link Budget: Uplink		
Earth radius	6371	km
Satellite height	35786	km
Satellite distance	37221	km
Carrier frequency	800	MHz
Noise bandwidth, B	180000	Hz
Free space path loss	182	dB
Boltzmann constant k	1,38E-23	J/K
T_system	827	K
k* T* B	-116,9	dBm
Receiver noise floor	-116,9	dBm
Required SNR	3	dB
Receiver sensitivity	-113,9	dBm
TX EIRP	35	dBm
RX antenna gain	36	dBi
Interference margin	3	dB
Maximum path loss	181,9	dBm

Terminal antennas

A typical terminal antenna solution for L-Band and S-Band is a (passive) quadrifilar helix or patch antenna. Active antenna technology requires power input, therefore, therefore, they are feasible only in special cases. Typical quadrifilar helix antenna at this frequency range is about the length of 10-20 centimeters, diameter varies from one to several centimeters. The radiation pattern of the quadrifilar helix is typically designed so, that the best gain is about 120 degrees (+/- 60 degrees upwards) from the tip of the antenna, so in general the device needs just to point upwards, but in higher latitudes it needs to be tilted if the geostationary satellite is in question. A major advantage of a quadrifilar helix is its very wide angle circular polarization.

Patch antennas can be described as a square or flat panel. Both passive and active models exist currently and are commercially available from multiple vendors. In comparison to a helix, a patch antenna gives more directional beam, and so there is less gain demand for the transmitter, but as a down side the patch antenna needs to be more carefully directed towards the desired satellite. Also a circular polarization can be realized with a patch, but typically the beam (cone), where the circular polarization is good, is much narrower than that in a quadrifilar helix. An example of a patch antenna is shown in Figure 4.7.2.

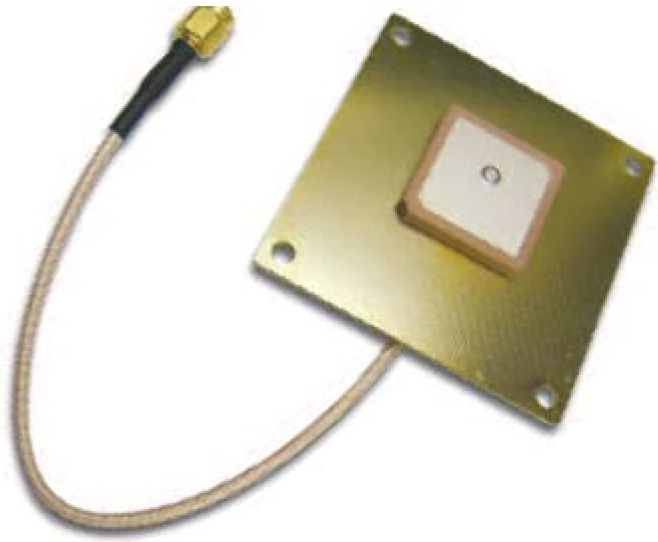


Figure 4.7.2: Example of a patch antenna.

A major issue in terminal design is the cable loss, which limits the achievable length of the cable. Within L-Band frequency of roughly 1.6 GHz the practical loss should be less than 3 dB. Table 4.7.5 lists the losses of different cable types.

Table 4.7.5: Cable loss estimates.

	Loss in [dB] @ 1600 MHz			
Length [m] / Cable type	RG59	RG6	RG7	RG11
5	1,71	1,37	1,09	0,93
10	3,43	2,74	2,18	1,87
20	6,85	5,49	4,35	3,73

4.7.6 Spectral efficiency, air interface capacity

As discussed before, Vattenfall customer devices locate predominantly in rural areas with an average of only 14 customer sites per MV/LV transformer. Therefore, Vattenfall has preferred wide area, low capacity cellular GPRS as the primary meter access technology. There are roughly 400 000 customer devices, which are spread over a large geographical area (see Chapter 4.1).

In satellite based communication, the entire Vattenfall network is served by a single satellite beam (base station). During Sylvi storm the highest rate of power outages was 15000 outages / 15 min across the VFV system. This corresponds to around 17 faults per second (1000 faults per minute). If we assume that each fault is reported by a data package of 150 bytes (1200 bits, SMS type data packet), the needed peak data rate for a worst case scenario is roughly 20.4 kbit/s (17*150*8 bits/s). This takes 17*10 RB's, which covers 170 ms in time. The required amount is 170 RB's out of 6000 available ones in one second. The SG data rate is therefore rather small even in a worst scenario of a very strong storm. Therefore, only about 3% of system throughput is estimated to be used (in “storm scenario”). It must be noted that this calculation does not take into account the control signaling overhead.

In a normal operation mode AMR requires roughly 400 000 data reports per 6 hours (see 4.3.1). This scales to 22.2 kbit/s on average, if each reading requires 1200 bits. From the 700 kbps system throughput the AMR data takes only about 3%. Again, this calculation does not take into account the control signaling overhead.

In general, the spectrum efficiency is rather modest in current scenario since roughly 0.7 Mbit/s is reached at 1.4 MHz channel. This low efficiency of 0.5 bit/s/Hz is mainly due to low SNR condition in two-way satellite communications which prevents the use of high modulation and coding schemes. Table 4.7.6 below summarizes the findings.

Table 4.7.6. SG data rate requirement.

Required SG data capacity (1.4 MHz LTE bandwidth)			
Scenario	***Required data rate D***	***Throughput T***	***D/T***
Peak fault case	20.4 kbit/s	720 kbit/s	2,80%
Average AMR case	22.2 kbit/s	720 kbit/s	3,1%

4.7.7 Observations

Satellite based SG data transfer is in principle feasible for both GEO and LEO satellite systems. In extreme weather conditions, it could be the only system that is operating due to the fact that terrestrial base stations are vulnerable to lightning etc. However, it was evaluated that the required SG data rate is very small for a network of 400000 field devices. This indicates that for cost reasons the SG data transfer should be only a small part of a hybrid terrestrial/satellite LTE network.

The satellite approach has a specific challenge for the MAC layer processing since a single satellite cell would cover a large number of field devices (400000 in the current case). It is not clear whether this number of users can be in a connected state. Perhaps some form of time multiplexing between idle and connected states is needed to reduce the MAC layer requirements.

Satellite links comprise large propagation path loss (low SNR) which indicates that small bandwidths and low modulation and coding schemes are preferable. On the other hand, this is not a severe limitation due to the fact that the SG data capacity need is small. The spectrum efficiency tends to be very modest, thought, and e.g. the MIMO approach is not attractive.

5 Results

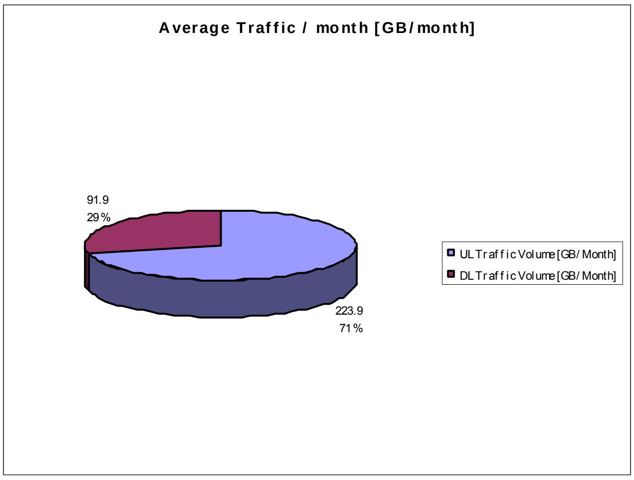
Unless sated otherwise the following results are for the dedicated LTE network which is coverage optimized for the utility. This is the worst case from a traffic load point of view due to the comparatively lower number of sites and cell / network capacity when compared with the CSP MBB network.

5.1 Uplink vs. Downlink traffic ratio

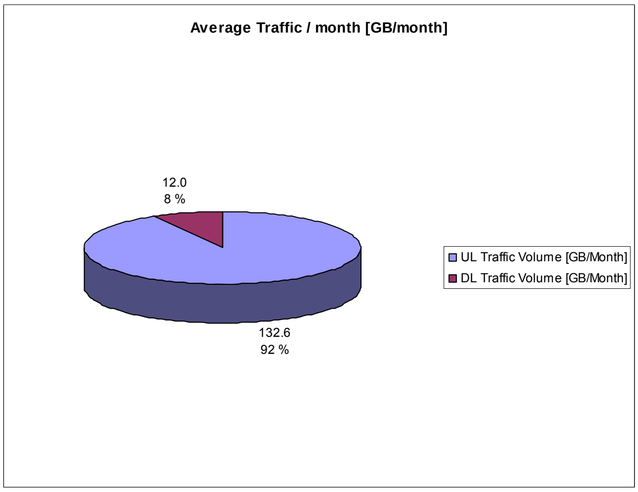
The following charts compare the Uplink vs. Downlink ratio from the average monthly traffic.

The traffic is calculated for the air interface and includes RRC signalling and protocol overheads (see 4.4.2).

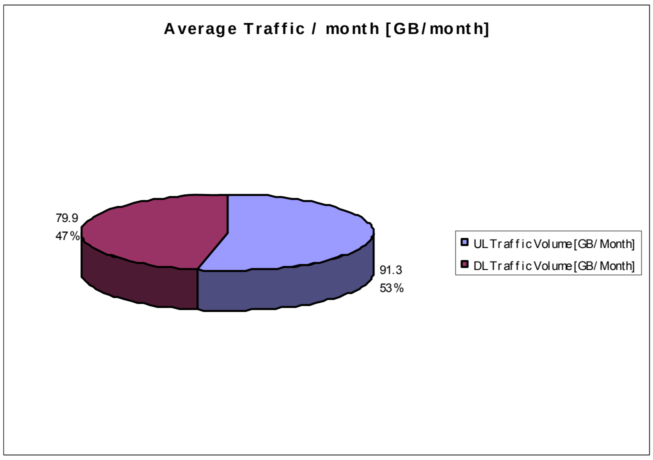
All use cases combined:



AMR only:



DA use cases (without AMR):



The large UL - DL asymmetry in the AMR case is due to the assumed ~11:1 asymmetry of the meter reports.

For the DA related use cases comprising many low-volume signaling events, the combined effect of symmetric load from ICMP pings, TCP/IP and VPN overheads as well as RRC signaling for disconnectors tend to level this difference to nearly 50:50%.

It is sometimes argued that LTE TDD has an advantage over FDD in matching asymmetric UL traffic needs. While this is true, TDD also has a worse radio link budget and hence less cell coverage, see [2]. This would drive the cost of a dedicated utility LTE TDD network compared to FDD as these networks are strictly coverage limited (see following results on low the capacity utilization).

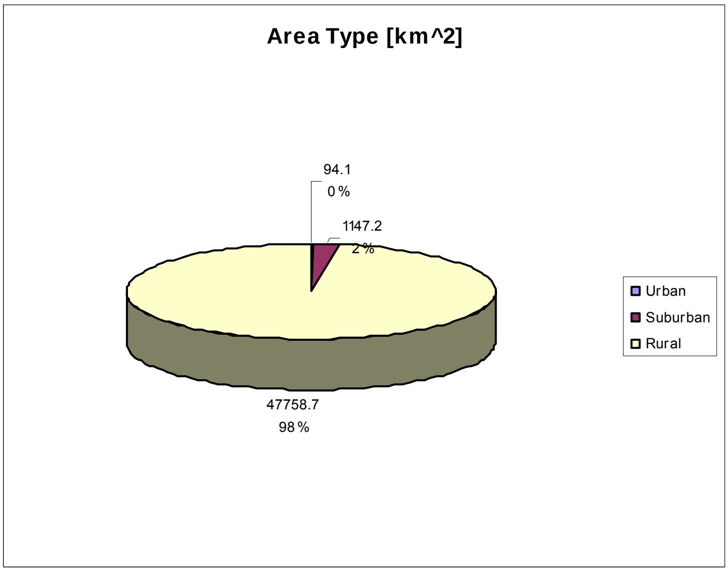
As SG traffic stresses the UL much more than the DL, there is no gain (but only extra cost) from the additional eNB TX paths needed for MIMO in a dedicated utility optimized LTE network. Note however, that a CSP provided MBB network would anyway deploy MIMO in order to boost DL user throughput.

As UL is clearly the limiting direction, both from an offered SG traffic and LTE capacity perspective, most of the following traffic load results will be quoted for UL only.

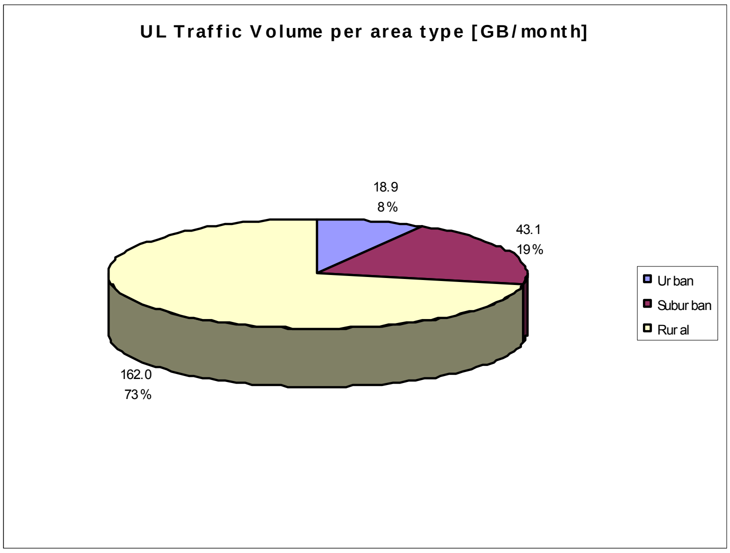
5.2 Traffic per area type

The following 2 charts show the geographical area type distribution and then the distribution of the average monthly UL air interface traffic per area type.

Geographical area type distribution



Distribution of the average monthly air interface traffic per area type



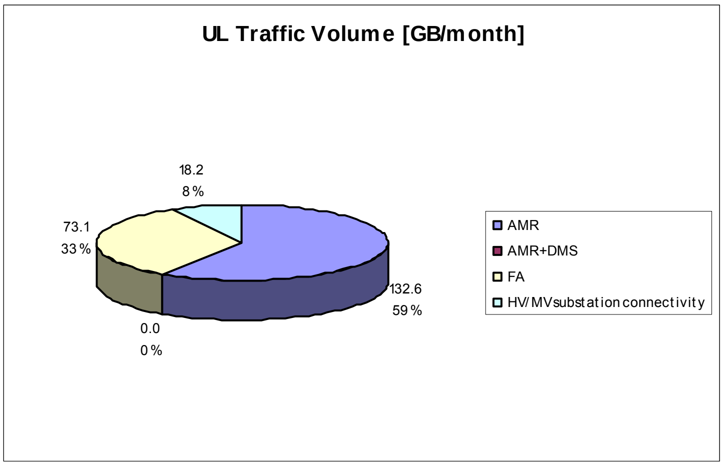
This is due to the fact that almost 35% of all meters are located in urban and suburban areas and AMR related traffic is the dominating traffic source.

5.3 Monthly traffic volumes

The following charts analyze the average monthly air interface traffic. The traffic is calculated for the UL and includes RRC signalling and protocol overheads (see 4.4.2).

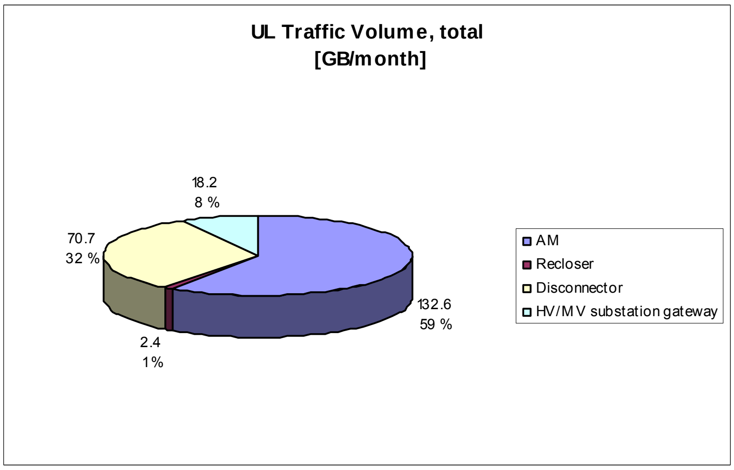
The breakdown of the total monthly air interface traffic on a per use case basis shows AMR dominates with nearly 60%, but that the 40% share of DA (= FA + primary substation connectivity) is significant. On the other hand, the AMR+DMS use case (using meter alarms & queries in DMS) generates insignificant traffic volumes due to the comparatively low event intensities scaling with fault rates:

Total monthly air interface traffic – per use case



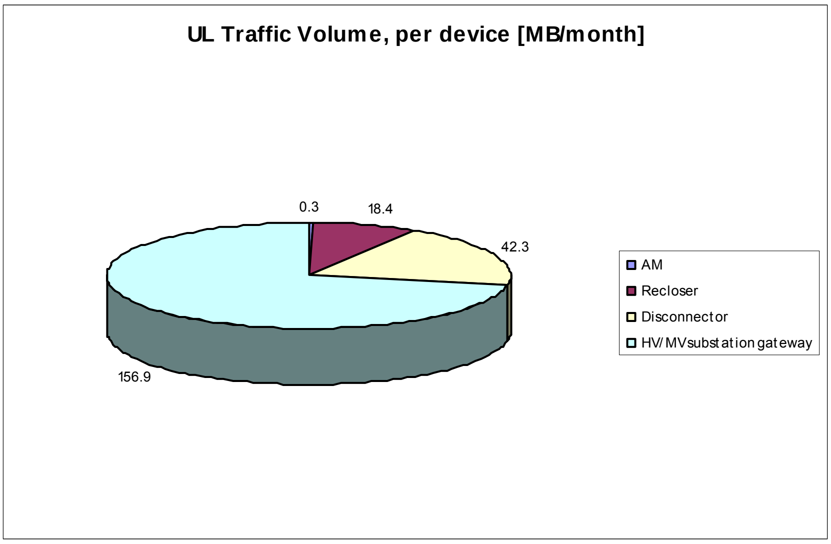
The corresponding picture emerges for the breakdown on a per field device type basis. The share from disconnectors is much larger than from reclosers; this is due to their comparatively larger numbers in the field (about one order of magnitude (OM)) and due to the large RRC signaling overhead for each VPN ping (establish & tear down of radio link).

Total monthly air interface traffic – per field device type

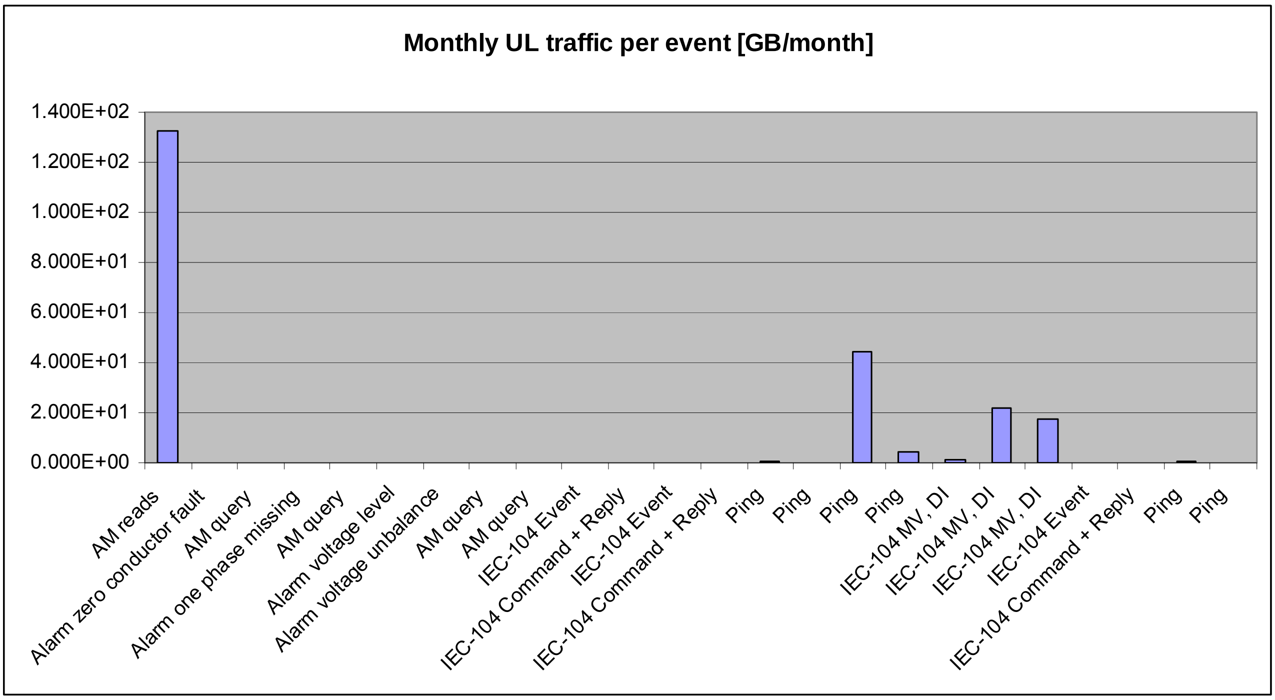


There are only round ~2k DA RTUs compared to the ~400k meters - a difference of 2 orders of magnitude (OMs). However, each DA RTUs generates much more traffic than a meter as can be seen from the breakdown of the monthly air interface traffic on a single field device basis. In particular the primary substation GW generates large traffic volumes, but there are only relatively few of them, so that their overall share on the total traffic volume remains under 10%. The traffic volume per each meter is small, but their large number generates the dominating share on the total traffic volume.

Monthly air interface traffic – for a single field device



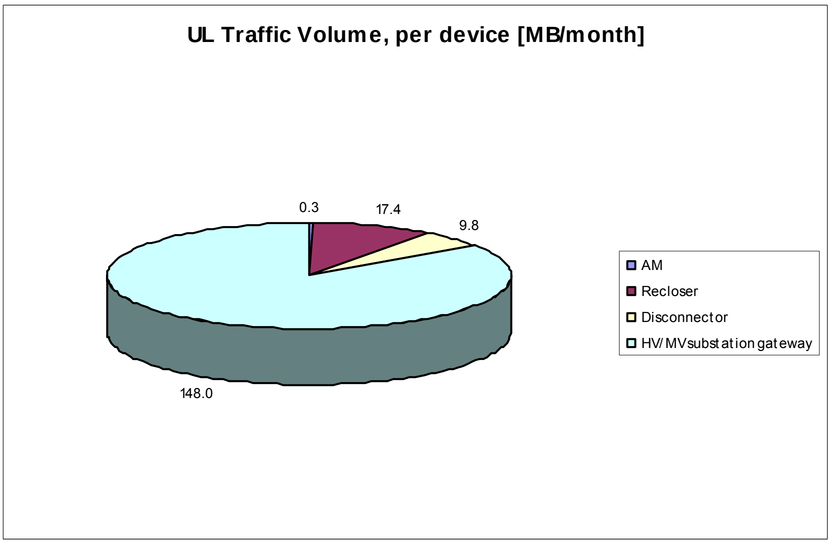
The following chart shows the breakdown of the total monthly air interface traffic on a per event basis:



Aside from AM reads, the disconnector VPN pings with their large RRC signaling overhead needed for establishment & tear down of the radio link are the second significant traffic source. Within the volumetric model here (see Sect. 4.4.2) each disconnector VPN ping generates 4x the amount of air-interface traffic compared to a recloser or substation VPN ping – for the latter ones it is assumed that the radio link is kept always active (i.e. in the RRC_CONNECTED state) due to the comparatively shorter event inter-arrival times. Hence the relative overhead of the disconnector VPN pings is assumed much larger. The only other significant traffic sources are recloser and substation IEC-104 measurements and state indications. These occur on a regular basis and not only in the (relatively rare) case of MV faults.

The following chart presents the monthly UL traffic at the P-GW APN on the basis of a single field device. This traffic does not include any RRC or other air-interface related protocol overheads; neither are transport overheads below the IP layer included.

Monthly traffic at the LTE P-GW APN – for a single field device



These results allow the correlation of the per-device traffic assumptions of Sect 4.4 against a few actual reported data points for disconnectors and reclosers as follows. Considering the UL vs. DL traffic ratio for FA (see chart in Sect 5.1), one obtains

- Recloser: **30 MB/month** transferred in total (UL+DL)
- Disconnector: **19 MB/month** transferred in total (UL+DL)

This calculated traffic is ~2.5 … 3.3 x smaller than actual measured monthly traffic which might be due to the missing overheads from VPN connection re-establishments, possibly differently configured field RTUs with higher reporting rates etc. Nevertheless, while this error sounds large, it seems acceptable for 'order-of-magnitude' estimates and will have little impact on the overall conclusions. Significantly more work would be required to obtain detailed data from the two underlying GPRS networks for better calibration; moreover to resolve the data volume on the granularity of individual events also measurements from SCADA/DMS and the AMR MDMS would be required.

Finally the average monthly air interface traffic will be set into relation to the LTE air interface capacity for each of the area types. Here system wide averages across all sites are computed. Figures for both, the dedicated LTE network optimized for utility as well as the CSP provided LTE MBB network according to the network capacity assumptions of Sect. 4.5.6 are presented:

Average monthly air interface traffic - Dedicated network optimized for utility

	UL Traffic Volume [GB/Month]						DL Traffic Volume [GB/Month]				
Average Traffic / month	Urban	Suburban	Rural	Total			Urban	Suburban	Rural	Total	
	58.24	132.90	500.05	**691.20**	**kbps**		8.14	49.85	225.61	**283.60**	**kbps**
Total offered events / traffic	18.9	43.1	162.0	**223.9**	**GB/Month**		2.6	16.2	73.1	**91.9**	**GB/Month**
LTE air interf. capacity	17600.5	29780.8	32321.9	79703.1	GB/Month		34896.7	62359.4	101598.3	198854.4	GB/Month
Capacity utilization, %	0.107	0.145	0.501	**0.281**	%		0.008	0.026	0.072	**0.046**	%

Average monthly air interface traffic - CSP provided LTE MBB network

	UL Traffic Volume [GB/Month]						DL Traffic Volume [GB/Month]				
Average Traffic / month	Urban	Suburban	Rural	Total			Urban	Suburban	Rural	Total	
	58.24	132.90	500.05	**691.20**	**kbps**		8.14	49.85	225.61	**283.60**	**kbps**
Total offered events / traffic	18.9	43.1	162.0	**223.9**	**GB/Month**		2.6	16.2	73.1	**91.9**	**GB/Month**
LTE air interf. capacity	261303.5	417785.1	1805466.8	2484555.4	GB/Month		449765.6	827161.9	3784982.6	5061910.1	GB/Month
Capacity utilization, %	0.007	0.010	0.009	**0.009**	%		0.001	0.002	0.002	**0.002**	%

It's evident that the average capacity utilization for the considered use cases is very low indeed, in particular for the CSP network.

The following sections investigate if this conclusion changes when considering peak traffic loads by zooming into much shorter time-scales on an hourly basis ('Busy hour', (BH)) and peak second basis.

5.4 Busy hour (BH) traffic

The BH as compared to an average hour is characterized by

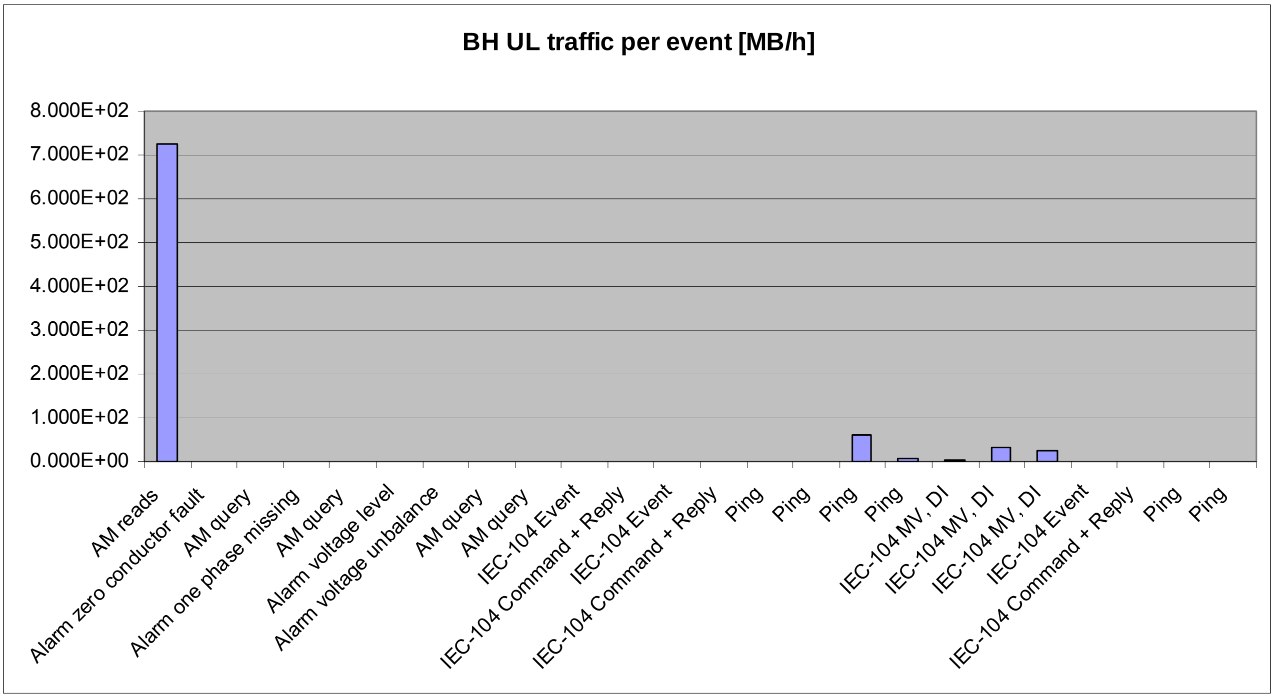
- AMR activity is ongoing, i.e. an hour within the assumed 6 h AMR read interval is picked. This means meter activity increases 24/6 = 4x in the BH as compared to a monthly average hour.
- Sylvi storm is ongoing, i.e. elevated faults rates at the worst hour of Sylvi storm are assumed, see Sect 4.2 for the detailed derivation of the relevant Peak-to-Average Event Rates multipliers.

The increased traffic activity of the BH as compared to an average hour is captured by the BH Peak-to-Average Event Rates multipliers PAER_BH provided in Table 4.2.4-1.

It should be noted that the offered traffic within the BH is of course by no means constant over time, but instead fluctuates randomly as events arrive. For example, a cluster of AM alarms, sent within a short period of time, could lead to much higher second-scale peak loads when compared to the average BH load. 'Peak second' load is considered in Sections 5.6 and 5.6.

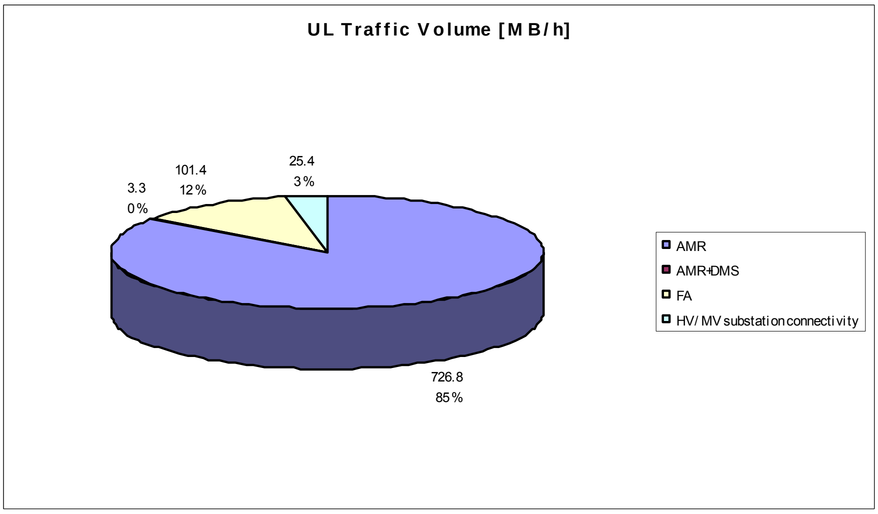
In the following selected results for the total air interface traffic with focus on differences to monthly averages will be shown. The BH traffic is calculated for the UL and includes RRC signalling and protocol overheads (see 4.4.2).

The following chart shows the breakdown of the BH air interface traffic on a per event basis.

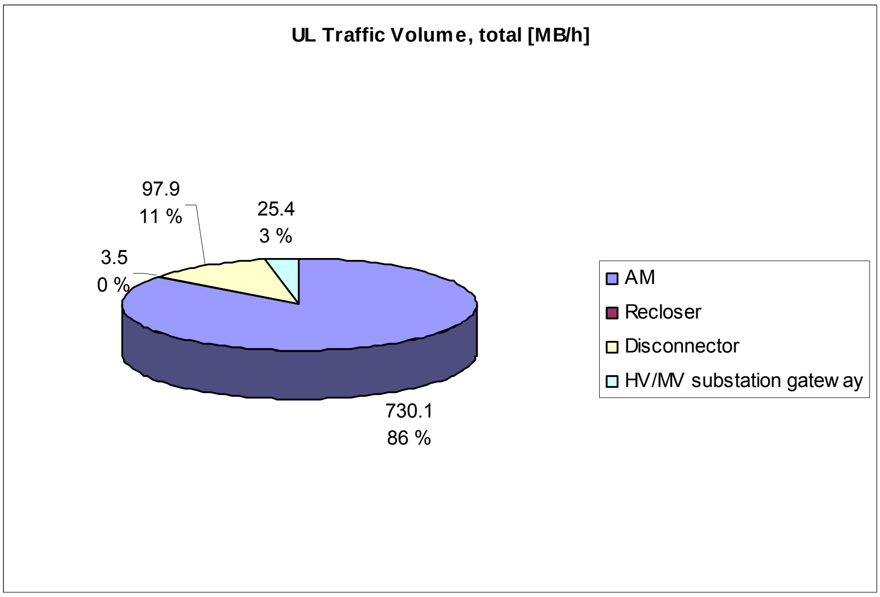


While the AMR traffic increases indeed by factor 4x during the BH when compared to a monthly average hour, the scheduled disconnector VPN pings as well as regular recloser & substation IEC-104 measurements don't scale upwards at all. Furthermore, storm related IEC-104 events & commands have still not become visible (on this scale). This makes the BH AMR share of the traffic even more dominating (when compared to the average hour) as the following charts demonstrate:

Total BH air interface traffic – per use case



Total BH air interface traffic – per field device type



The system wide average of the LTE air-interface capacity utilization remains quite low also during the BH:

BH air interface traffic - Dedicated network optimized for utility

	UL Traffic Volume [MB/h]						DL Traffic Volume [MB/h]				
Busy Hour Traffic	Urban	Suburban	Rural	Total			Urban	Suburban	Rural	Total	
	217.99	390.96	1295.29	**1904.24**	**kbps**		22.74	73.14	303.96	**399.85**	**kbps**
Total offered events / traffic	98.1	175.9	582.9	**856.9**	**MB/h**		10.2	32.9	136.8	**179.9**	**MB/h**
LTE air interf. capacity	24445.1	41362.2	44891.5	110698.8	MB/h		48467.6	86610.2	141108.8	276186.6	MB/h
Capacity utilization, %	0.401	0.425	1.298	**0.774**	%		0.021	0.038	0.097	**0.065**	%

BH air interface traffic - CSP provided LTE MBB network

	UL Traffic Volume [MB/h]						DL Traffic Volume [MB/h]				
Busy Hour Traffic	Urban	Suburban	Rural	Total			Urban	Suburban	Rural	Total	
	217.99	390.96	1295.29	**1904.24**	**kbps**		22.74	73.14	303.96	**399.85**	**kbps**
Total offered events / traffic	98.1	175.9	582.9	**856.9**	**MB/h**		10.2	32.9	136.8	**179.9**	**MB/h**
LTE air interf. capacity	362921.5	580257.1	2507592.8	3450771.4	MB/h		624674.4	1148836.0	5256920.2	7030430.7	MB/h
Capacity utilization, %	0.027	0.030	0.023	**0.025**	%		0.002	0.003	0.003	**0.003**	%

Compared to a monthly average hour, the system wide BH throughput went up by a factor of only ~2.8. Apparently the AMR related increase by 4x has been ‘diluted’ by very marginal increases for the DA use cases. This will be further investigated in the following section.

5.5 Increase of BH Signalling during 2010 Storms

The results of Section 5.4 showed that the system wide average of the LTE air-interface capacity utilization remains quite low - also during the BH. This happens despite the fact that the faults rates are significantly elevated during the worst hour of the Sylvi storm.

As a reminder, in Section 4.2.2 it was found that during the worst hour of Sylvi the Peak-to-Average Event (=fault) Rate increased in the time domain by a factor of ~431 compared to the average hour:

Hourly peak fault frequency, within whole system area, during Sylvi storm	Urban	Suburban	Rural	Total		PAER_time	PAER_area
Customer outage notice	4.4	13.9	540.3	**558.6**	f / h	674.1	2.4
LV zero conductor fault	0.2	0.8	29.5	**30.5**	f / h	674.1	2.4
LV one phase missing	2.5	7.9	307.0	**317.4**	f / h	674.1	2.4
LV voltage level	1.50E-04	4.67E-04	1.82E-02	**1.88E-02**	f / h	1.0	1.0
MV broken conductor	0.0	0.1	2.4	**2.4**	f / h	430.9	2.4
MV remaining faults	1.3	4.0	154.6	**159.9**	f / h	430.9	2.4

This results in the corresponding BH Peak-to-Average Event Rates multipliers PAER_BH as provided in Table 4.2.4-1:

Events & frequencies	Use cas	Field devi	PAER_BI
Alarm zero conductor fault	AMR+DMS	AM	674.1
AM query	AMR+DMS	AM	674.1
Alarm one phase missing	AMR+DMS	AM	674.1
AM query	AMR+DMS	AM	674.1
Alarm voltage level	AMR+DMS	AM	1.0
Alarm voltage unbalance	AMR+DMS	AM	430.9
AM query	AMR+DMS	AM	18.0
AM query	AMR+DMS	AM	674.1
IEC-104 Event	FA	Recloser	430.9
IEC-104 Command + Reply	FA	Recloser	430.9
IEC-104 Event	FA	Disconnector	430.9
IEC-104 Command + Reply	FA	Disconnector	430.9
Ping	FA	Recloser	1.0
Ping	FA	Recloser	1.0
Ping	FA	Disconnector	1.0
Ping	FA	Disconnector	1.0
IEC-104 MV, DI	FA	Recloser	1.0
IEC-104 MV, DI	FA	Disconnector	1.0
IEC-104 MV, DI	SS_CONN	GW_SS	1.0
IEC-104 Event	SS_CONN	GW_SS	430.9
IEC-104 Command + Reply	SS_CONN	GW_SS	430.9
Ping	SS_CONN	GW_SS	1.0
Ping	SS_CONN	GW_SS	1.0

The scheduled AMR traffic has a significant share of the total traffic and is not impacted by storms; hence we should isolate the increase (by 4x) of AMR during its BH from the storm related impact on the remaining use cases. Therefore we will focus in the following on those use cases which contain, at least partially, fault driven events, i.e. FA, primary substation connectivity (contains reclosing related IEC-104 events and commands) and AM+DMS (alarms, queries). That is to say all use cases combined, with the exception of AMR.

For this scenario the following figures are the total air interface traffic on UL and include RRC signalling and protocol overheads (see 4.4.2).

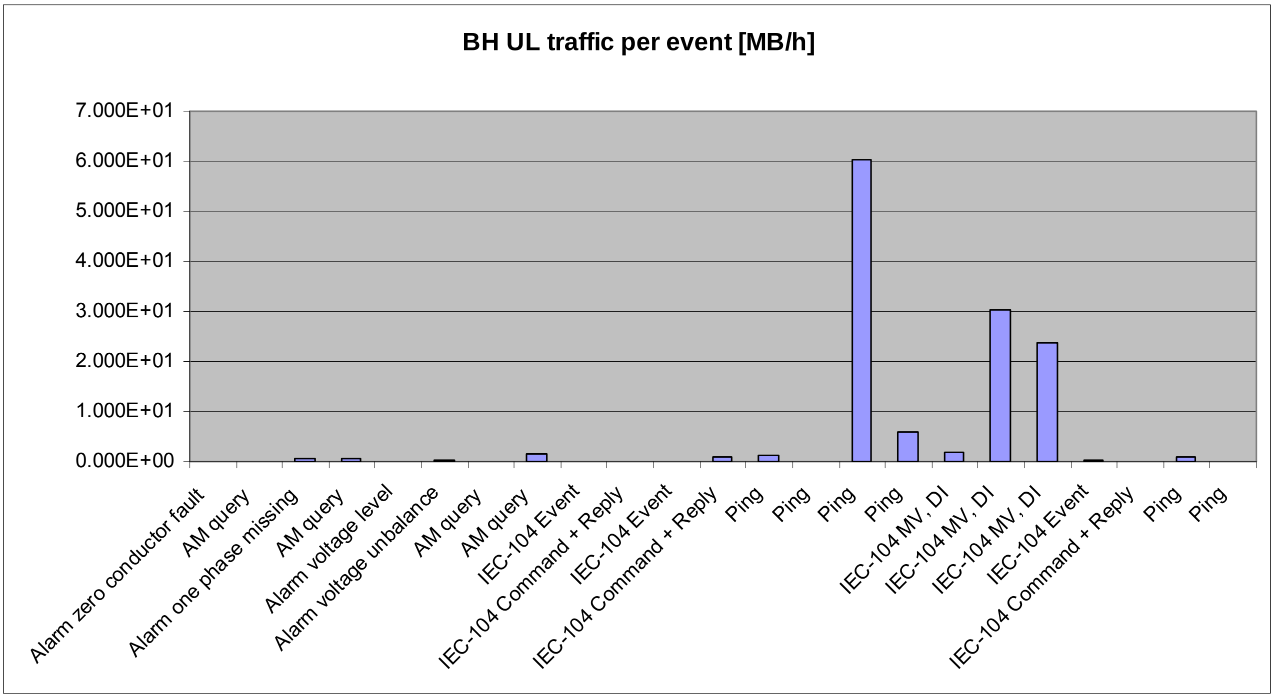
Total air interface traffic on UL - use cases combined, with the exception of AMR

	UL Traffic Volume [MB/h]				
Busy Hour Traffic	Urban	Suburban	Rural	Total	
Average hour:					
	4.01	44.65	229.30	277.96	kbps
Total offered events / traffic	1.8	20.1	103.2	125.1	MB/h
BH (during worst hour of Sylvi-storm):					
	4.26	45.22	239.69	289.17	kbps
Total offered events / traffic	1.9	20.4	107.9	130.1	MB/h

The increase of the total traffic during the worst hour of the Sylvi storm is merely 4%.

How is it possible that such a large increase of the event intensity, by more than 2 OM, can have such a small impact on the aggregate BH traffic?

The following chart shows the breakdown of the BH air interface traffic on a per event basis for these use cases:



Periodic VPN Pings and regularly sent IEC-104 measured values & digital state indications are the dominating traffic - even during the storm. On the other hand, fault related signalling (IEC-104 events & commands, AM alarms, queries…) does not increase to significant levels.

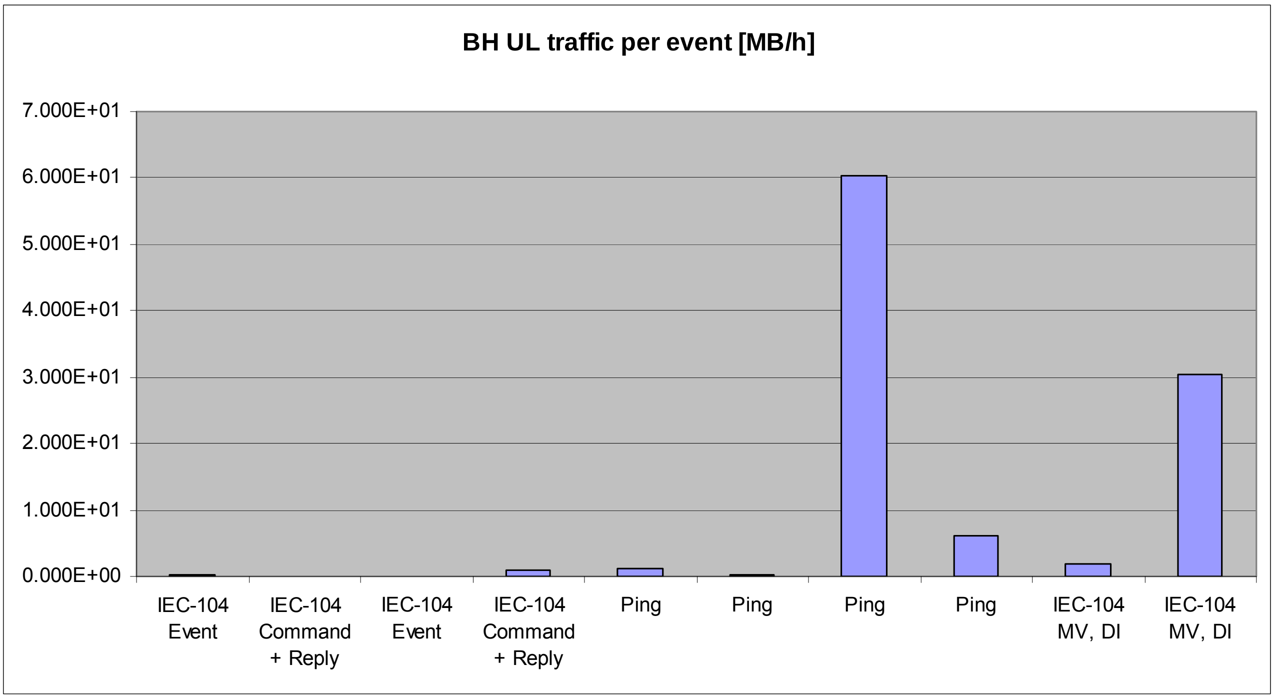
Periodic VPN Pings and regularly sent IEC-104 measured values & digital state indications provide a constant signalling baseload which masks the storm (fault) induced IEC-104 signaling.

In the following this will be analyzed in more detail for each of the use cases, FA, primary substation connectivity and AM+DMS.

The following table provides the FA related event occurrences during the worst hour of the Sylvi storm:

				Events / BH	Events / BH	Events / BH	Events / BH
Busy Hour Traffic	Use cas	Field devic	EPC transaction	Urban	Suburban	Rural	Total
IEC-104 Event	FA	Recloser	RRC_CONN	0	27	985	**1012**
IEC-104 Command + Reply	FA	Recloser	RRC_CONN	0	20	785	**805**
IEC-104 Event	FA	Disconnector	RRC	0	0	0	**0**
IEC-104 Command + Reply	FA	Disconnector	PAG_RRC	14	44	1727	**1785**
Ping	FA	Recloser	RRC_CONN	0	1800	6000	**7800**
Ping	FA	Recloser	RRC_CONN	0	180	600	**780**
Ping	FA	Disconnector	RRC	1200	18000	81000	**100200**
Ping	FA	Disconnector	PAG_RRC	120	1800	8100	**10020**
IEC-104 MV, DI	FA	Recloser	RRC_CONN	0	2520	8400	**10920**
IEC-104 MV, DI	FA	Disconnector	PAG_RRC	624	9363	42135	**52122**
Total offered events / traffic				1.958E+03	3.376E+04	1.497E+05	**1.854E+05**

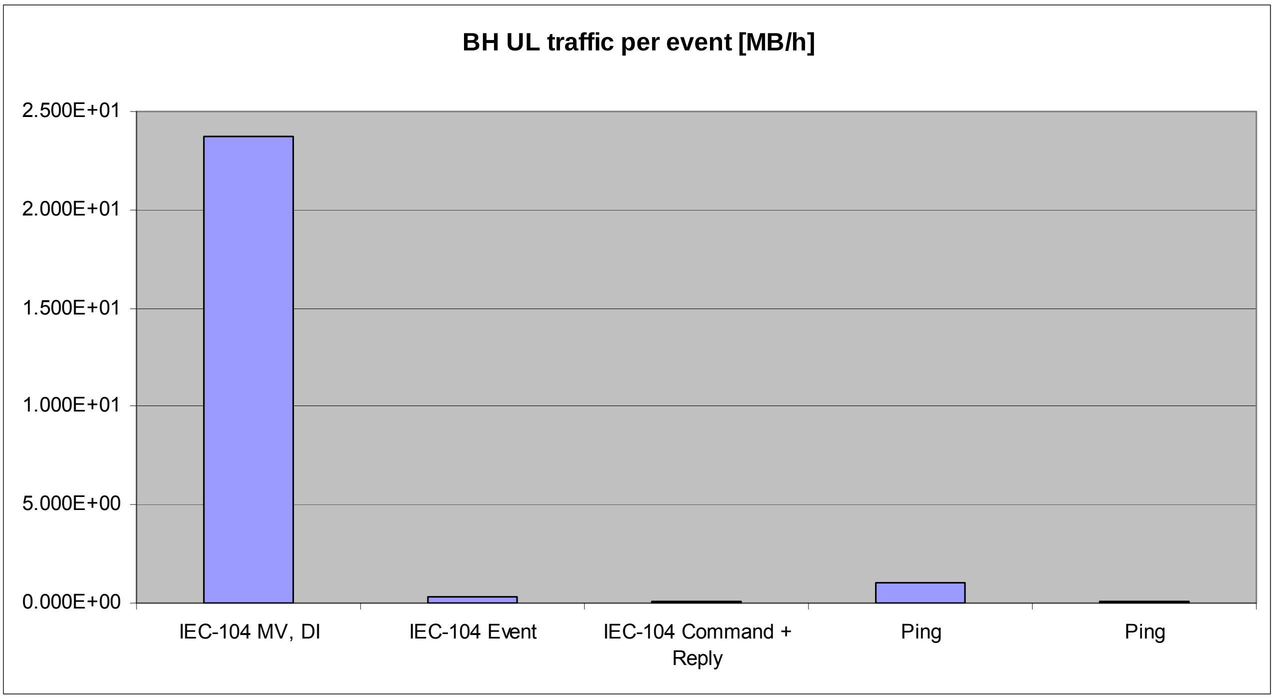
Pings and IEC-104 measured values remain the dominating events also during the storm. The resulting BH air interface traffic on a per event basis is shown in this chart:



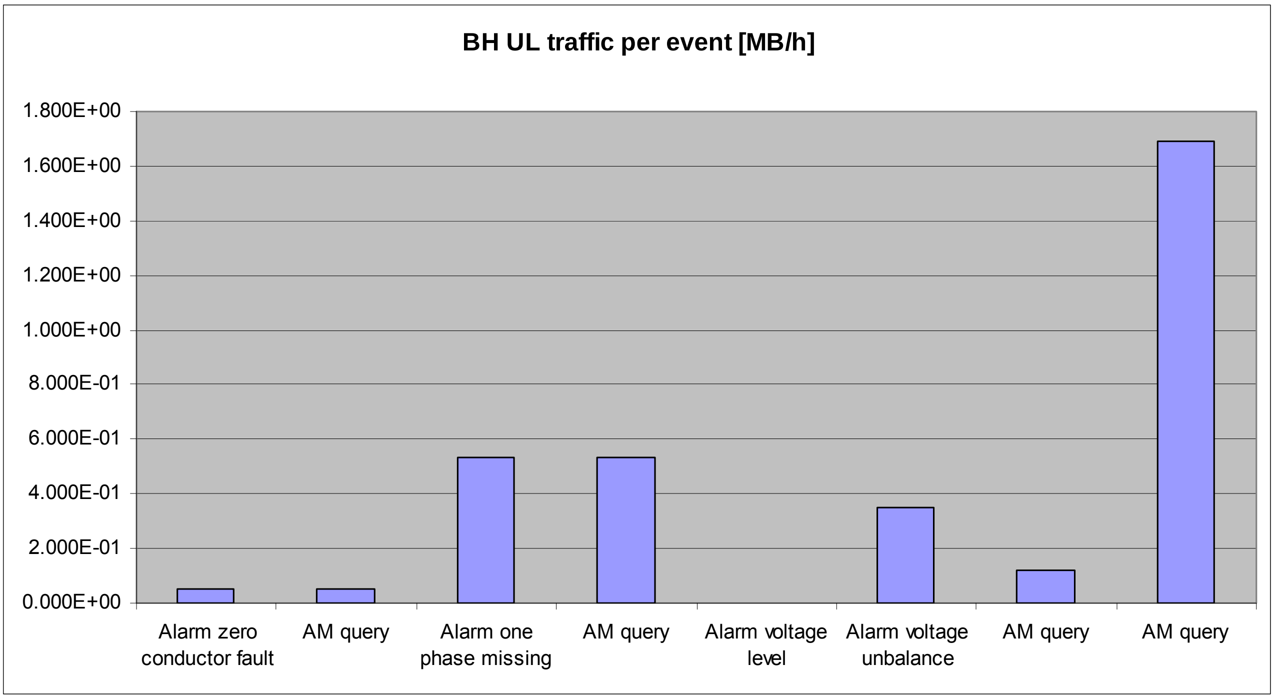
The following table provides the primary substation related event occurrences during the worst hour of the Sylvi storm:

Busy Hour Traffic	Use cas	Field devic	EPC transaction	Events / BH Urban	Events / BH Suburban	Events / BH Rural	Events / BH Total
IEC-104 MV, DI	SS_CONN	GW_SS	RRC_CONN	2520	7560	87360	**97440**
IEC-104 Event	SS_CONN	GW_SS	RRC_CONN	17	54	2498	**2569**
IEC-104 Command + Reply	SS_CONN	GW_SS	RRC_CONN	6	20	785	**812**
Ping	SS_CONN	GW_SS	RRC_CONN	180	540	6240	**6960**
Ping	SS_CONN	GW_SS	RRC_CONN	18	54	624	**696**
Total offered events / traffic				2.742E+03	8.228E+03	9.751E+04	**1.085E+05**

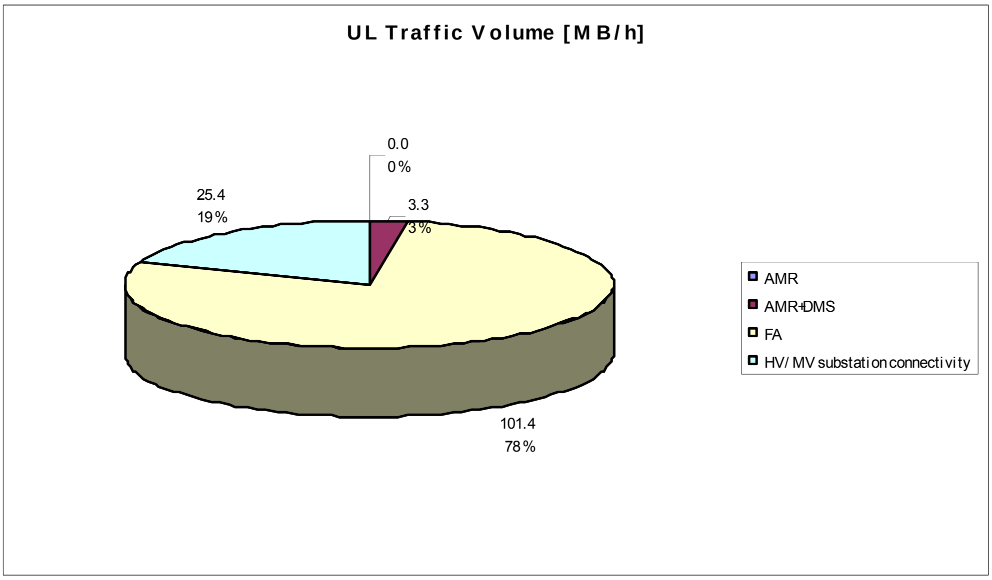
Regularly sent IEC-104 measured values remain the dominating events also during the storm. The resulting BH air interface traffic on a per event basis is shown in this chart:



The BH air interface traffic for AM+DMS on a per event basis is shown in this chart. All events are fault induced (as the dominating scheduled AMR traffic has been omitted from the breakdown):



However, as shown in the following chart, the share of the AM+DMS signaling traffic during the worst hour of the Sylvi storm remains just some below 3% of all traffic from the considered DA use cases (without AMR). Hence it has very little impact compared to the constant signaling baseload of VPN Pings and regularly sent IEC-104 measured values & digital state indications generated by the DA use cases.



And yet, good care has to be taken that the transmission of a larger number of *AM alarms*, e.g. ‘One phase missing’ is randomized within a time interval in order to avoid cell peak load on a second scale. In VFV network this is done by randomizing them within a 3 min time window [12] which appears to be sufficient to throttle peak loads.

Contrary to the BH *average* results presented here, the impact of a burst of temporally and spatially localized *AM queries* is actually the most critical event from a cell peak load perspective, I.e. a burst of queries which are dispatched quasi-simultaneously towards meters attached to the same cell. This will be investigated further in Section 5.7.

5.6 EPC peak load

Results for second-scale peak loads on the LTE core network (EPC) are presented in the following.

Used parameters are:

Parameters		
Outage percentile	1.00E-04	
# cells per tracking area	3	
S1 U-plane transport overhead	1.25	

The low # cells per tracking area is an optimization (reduction of paging load) for the dedicated network optimized for utility, bearing in mind that all terminals are stationary M2M devices which don't trigger frequent TA updates.

Events are modelled as independent Poisson arrivals (parameter *Outage percentile*) in order to capture statistical variations of the # of events per second. This is basically a valid assumption except for meter alarms and queries which are correlated events.

From a P-GW peak throughput perspective we obtain the following results:

	UL Traffic Volume [kbps]	DL Traffic Volume [kbps]	
Total offered events / U-plane traffic, average / s	1.575	0.156	Mbps
Total offered events / U-plane traffic, peak / s	**2.183**	**0.216**	**Mbps**
Total offered U-plane traffic, peak / s, including S1 transport overhead	**2.728**	**0.271**	**Mbps**
EPS U-plane capacity (dimensioned according to air interface average cell capacity @ 70% load)	232.1	579.0	Mbps
Capacity utilization	**0.941**	**0.037**	%

The following can be observed:

- the aggregate offered peak U-plane traffic including S1 transport overhead is merely in the order of a single DSL connection
- if the backhaul transport connections eNB ←→ S/P-GW would be dimensioned according to the air interface average cell capacity @ 70% load, then the capacity utilization would be < 1%. For a CSP MBB network this would be even significantly less.

Actual LTE/SAE S/P-GW would offer significantly higher throughputs in the multi-Gbps range, even in their minimum configuration. Hence, this offered M2M traffic **is ~3 OM less** than a single S/P-GW in a minimum configuration would be able to offer.

The following table summarizes the peak transactions per second (TPS) and session context requirements:

Paging messages	RRC state transitions	Dedicated bearer act/deact	Total	
77.95	177.29	0.00	255.23	1/s
# of EMM registered devices			364747	
# of PDN connections, default bearers			364747	
# of eNBs			60	

Strictly speaking there could be a few more TPS considering that not all the events are actually independent: meter alarms and queries occur in ‘bursts’, triggered by a single fault. If we assume that within the considered peak load second 6.25% of AM on a rural MV feeder are queried after a MV fault has been repaired then this would lead to a burst of 0.9*0.0625*412 = ~23 AM queries / s. Within the allotted outage percentile there might happen still a few other meter queries within the same considered peak load second, perhaps not more than ~10 though. All in all, for a worst case second, we might therefore still add 23 + 10 = 33 events which gives rise to 66 RRC state transitions and 99 paging messages or additional 165 TPS giving a **grand total of 420 TPS.**

Now this **is still ~2 OM less** than typical MME nodes will be able to handle in their minimum configuration.

However, the # of EMM registered devices (sessions) in the order of 365k is quite significant when comparing to the # of pops covered by a MBB network in the same area. This requires the corresponding significant memory resources within the nodes and registers to store the session and bearer contexts, mainly those related to the meters.

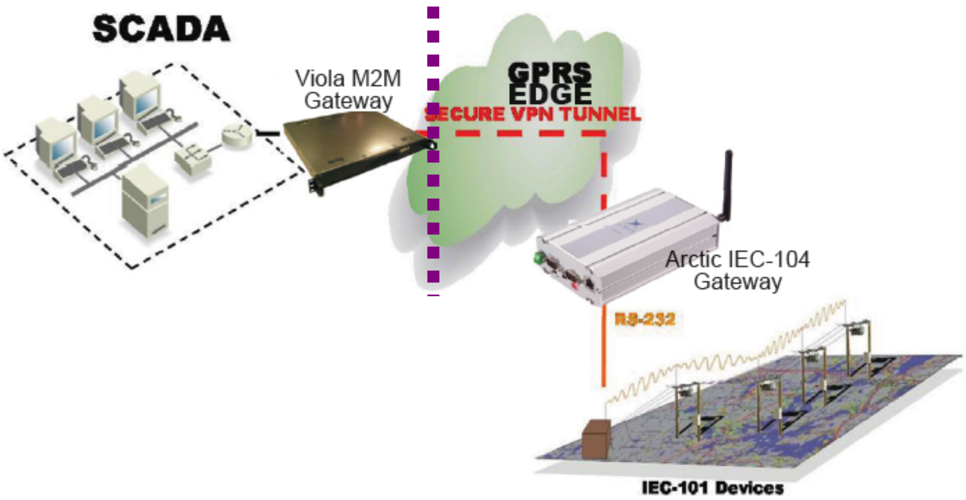
We conclude that the VFV scenario traffic impact on EPC capacity is essentially marginal in terms of throughput and TPS, however significant, due to AMR, in terms of session and context storage requirements.

This is repeating the old expectation that M2M devices tend to be numerous, yet generate very little activity per device.

Hence, their traffic characteristics departs significantly from that of MBB devices (smart phones, dongles) and can lead to challenges in economically (down-)scaling of EPC nodes designed for MBB networks when deployed in networks dominated by M2M traffic.

5.7 M2M Gateway peak load (for DA use cases)

Results for second-scale peak loads on the M2M gateway are presented in the following. The considered use cases are FA and primary substation connectivity.

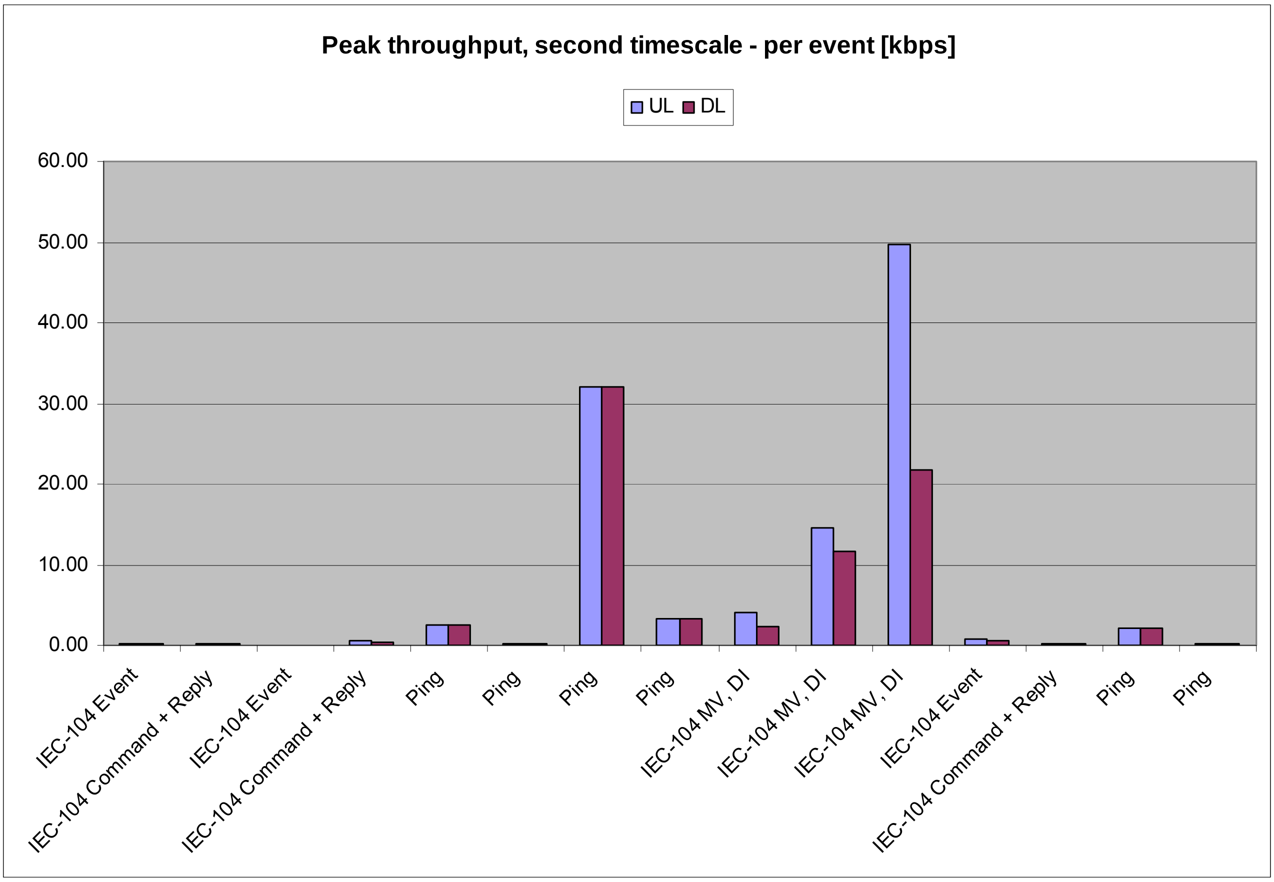


Events are modelled as independent Poisson arrivals (@ outage percentile = e-4) in order to capture statistical variations of the # of events per second. This is basically a valid assumption for the DA use cases.

Transport overhead (e.g. related to Ethernet, possibly IPSec) between the P-GW APN and the M2M gateway is *not* included and may be up to an additional 25%.

			UL Traffic Volume [kbps]	DL Traffic Volume [kbps]	
Peak second Traffic	**Use cas**	**Field devic**	**Total**	**Total**	
IEC-104 Event	FA	Recloser	**0.28**	**0.22**	kbps
IEC-104 Command + Reply	FA	Recloser	**0.22**	**0.21**	kbps
IEC-104 Event	FA	Disconnector	**0.00**	**0.00**	kbps
IEC-104 Command + Reply	FA	Disconnector	**0.50**	**0.48**	kbps
Ping	FA	Recloser	**2.50**	**2.50**	kbps
Ping	FA	Recloser	**0.25**	**0.25**	kbps
Ping	FA	Disconnector	**32.06**	**32.06**	kbps
Ping	FA	Disconnector	**3.21**	**3.21**	kbps
IEC-104 MV, DI	FA	Recloser	**4.13**	**2.43**	kbps
IEC-104 MV, DI	FA	Disconnector	**14.48**	**11.58**	kbps
IEC-104 MV, DI	SS_CONN	GW_SS	**49.80**	**21.65**	kbps
IEC-104 Event	SS_CONN	GW_SS	**0.71**	**0.57**	kbps
IEC-104 Command + Reply	SS_CONN	GW_SS	**0.23**	**0.22**	kbps
Ping	SS_CONN	GW_SS	**2.23**	**2.23**	kbps
Ping	SS_CONN	GW_SS	**0.22**	**0.22**	kbps
Total offered events / U-plane traffic, average / s			0.111	0.078	Mbps
Total offered events / U-plane traffic, peak / s			**0.159**	**0.112**	**Mbps**

The same data is visualized in the following chart:



IEC-104 control traffic (alarms, reclosing,…) plays only a minor role even though the elevated fault rates during the Silvy storm are assumed.

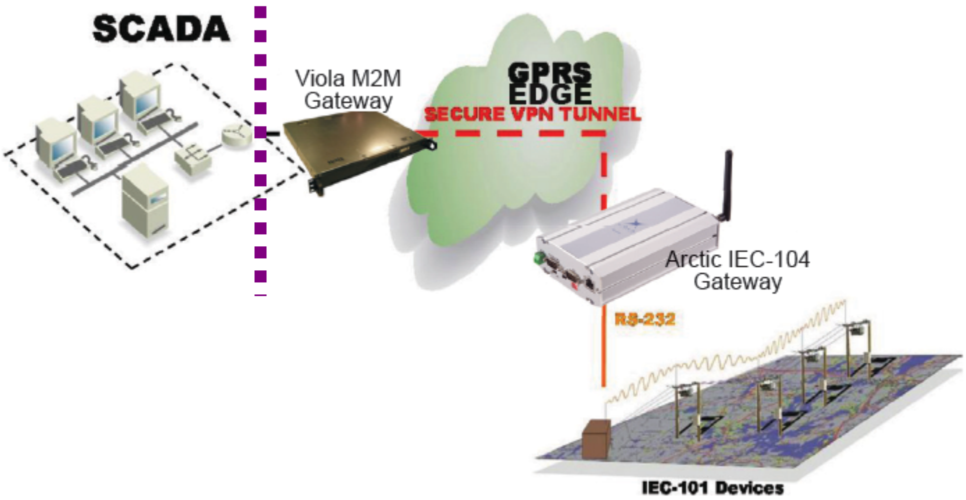
Most pings come from the disconnectors, yet these RTUs provide relatively little useful IEC-104 measurement data. For reclosers the overhead Pings vs. IEC-104 data is already lower and for the primary substation even less. This indicates that in order to end up with similar Ping overheads for RTUs the Ping frequency could be set in proportion to the useful IEC-104 traffic volume (which would reflect the relative importance of the RTUs in SCADA).

This calculated traffic is ~4 x smaller than actual measured traffic between APN and M2M gateway. This indicates that VPN related overheads are not completely accounted for e.g. due to missing overheads from VPN connection management and connection re-establishments.

Significantly more work would be required for better calibration, e.g. measurements and packet inspection at the M2M gateway.

5.8 SCADA Gateway peak load (for DA use cases)

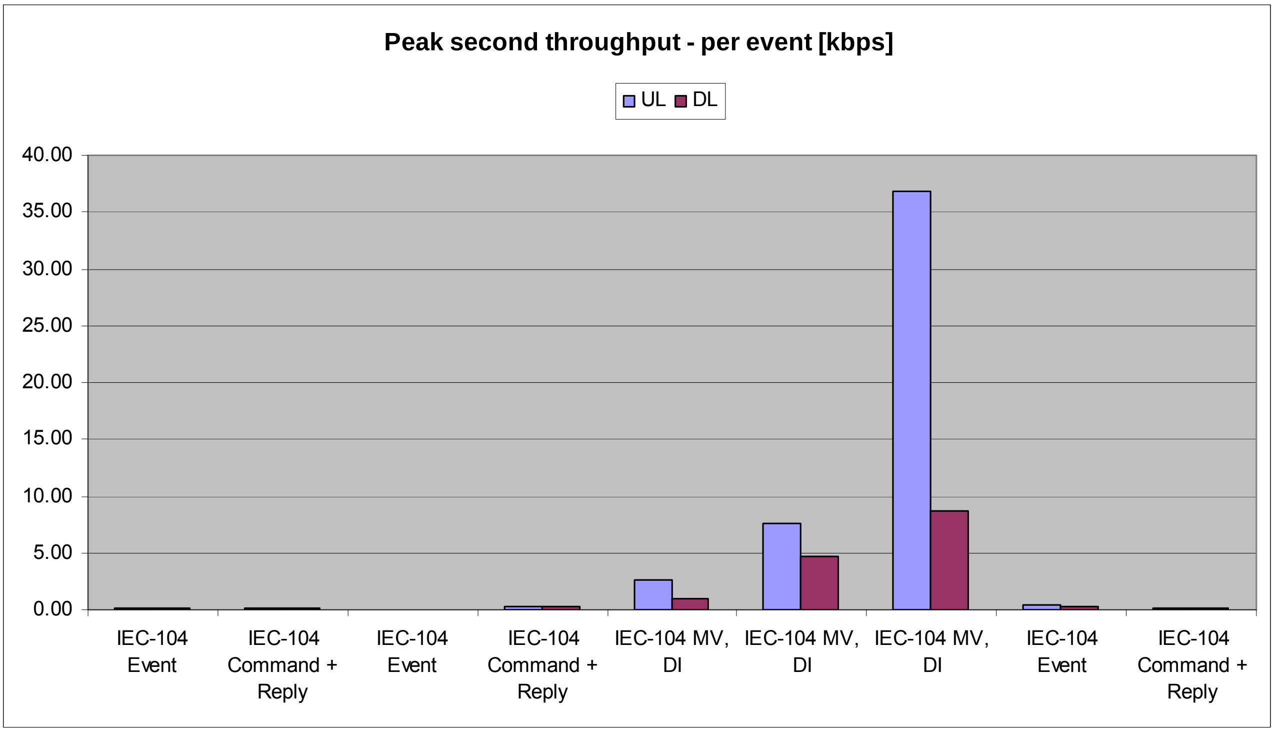
Results for second-scale peak loads on SCADA are presented in the following. Use case and event modelling is the same as in the previous section, however, now the VPN related overhead (SSH and VPN pings) is not present.



Ethernet transport overhead between the M2M gateway and SCADA is *not* included and may be up to an additional ~25%.

			UL Traffic Volume [kbps]	DL Traffic Volume [kbps]	
Peak second Traffic	Use cas	Field devic	Total	Total	
IEC-104 Event	FA	Recloser	0.15	0.09	kbps
IEC-104 Command + Reply	FA	Recloser	0.12	0.11	kbps
IEC-104 Event	FA	Disconnector	0.00	0.00	kbps
IEC-104 Command + Reply	FA	Disconnector	0.26	0.24	kbps
IEC-104 MV, DI	FA	Recloser	2.67	0.97	kbps
IEC-104 MV, DI	FA	Disconnector	7.53	4.63	kbps
IEC-104 MV, DI	SS_CONN	GW_SS	36.81	8.66	kbps
IEC-104 Event	SS_CONN	GW_SS	0.37	0.23	kbps
IEC-104 Command + Reply	SS_CONN	GW_SS	0.12	0.11	kbps
Total offered events / U-plane traffic, average / s			0.048	0.015	Mbps
Total offered events / U-plane traffic, peak / s			**0.076**	**0.024**	**Mbps**

The same data is visualized in the following chart:



Overall aggregate UL throughput is in the order of 75 kbps, including Ethernet overhead perhaps ~100 kbps.

As before, IEC-104 control traffic (alarms, reclosing,…) plays only a minor role even though the elevated fault rates during the Silvy storm are assumed.

This calculated traffic ~2x smaller than actual measured traffic between M2M gateway and SCADA. This indicates that the model if the IEC-104 measurements, in particular for the primary substation, is not accurate. To better resolve the data volume on the granularity of individual events measurements from SCADA would be required.

5.9 Cell peak load

'Cell peak load' is here to be understood as the peak air interface traffic volume per second for a temporally and spatially worst loaded cell. This traffic includes RRC signalling and protocol overheads (see 4.4.2).

In the *spatial* domain we assume the *peak* amount of field devices within a cell. This peak amount is obtained from the average value by scaling with suitable spatial cell peak-to-average ratios (PAR); the detailed assumptions are provided in Section 4.5.5. Additionally, the Peak-to-Average Fault multipliers as defined for the utility service area affected by the storm are used; the detailed assumptions related to this aspect are provided in Section 4.2.3.

Events are modelled in the *temporal* domain as independent Poisson arrivals (parameter *Outage percentile*) in order to capture statistical variations of the # of events per second. Independence of Poisson arrivals is basically a valid assumption except for meter alarms and queries which and occur in 'bursts' triggered by a single fault and are therefore correlated events.

Parameters		
Outage percentile	1.00E-02	
RRC release timer	5	s

The following results will consider air interface peak loads for during a second and will be presented for the following two cases:

a) All signaling events are uncorrelated Poisson arrivals

b) Same as a), but then a worst case signaling burst will be added as (deterministic) load into this 'peak second'. The selected worst case is that of AMR+DMS queries in which 6.25% of AMs on a MV feeder are queried after a MV fault has been repaired. No other fault event of the considered use case creates such a large set of concurrent events within a small area.

The meter queries in case b) lead e.g. to a burst of 0.9*0.0625*412 = ~23 AM queries / s in a rural cell. In this we assume, as a worst case, that all queries are dispatched quasi-simultaneously and arrive within the considered peak load second. In reality some scheduling or randomization of the queries may be applied for peak load mitigation, but detailed information regarding actual algorithms has not yet been obtained.

Furthermore, assuming that the meter queries are concentrated around the MV fault location we find that 6.25% of the MV feeder length[3] is small enough to fall within a single cell of the CSP provided LTE MBB network[4]

[3] MV feeder lengths for the various area types are defined in Section 4.1

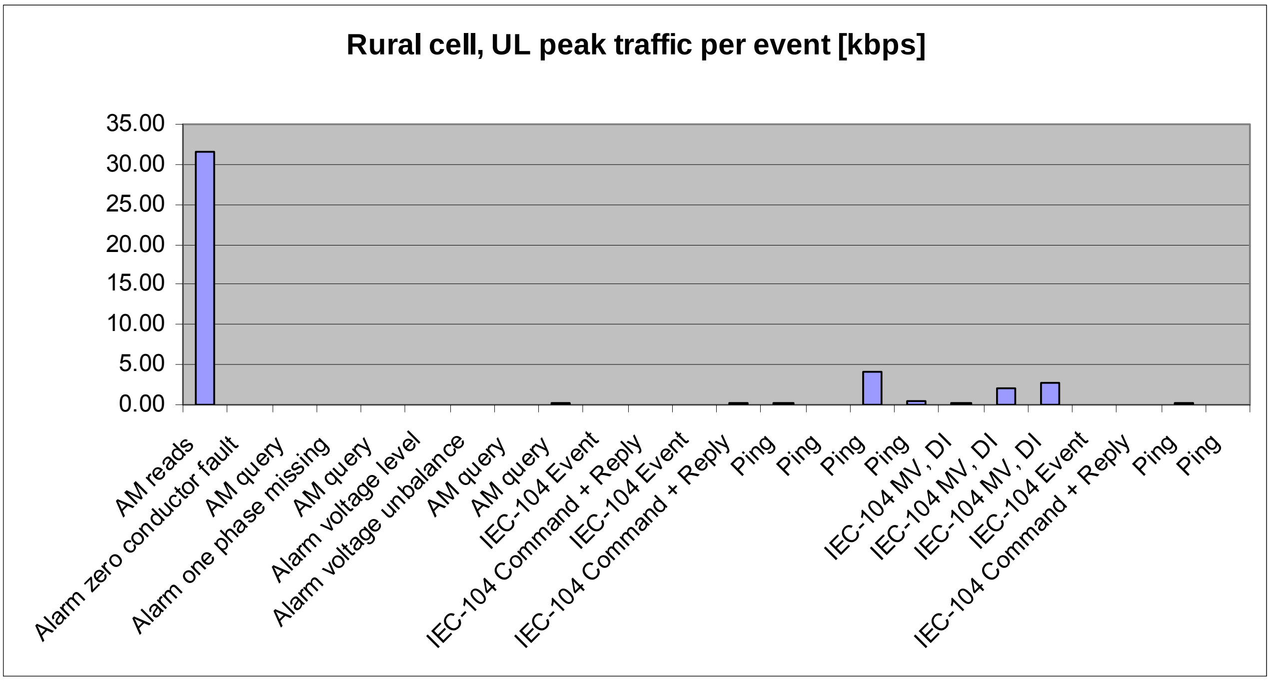
[4] and of course then even more so into the much larger cells of the dedicated network optimized for utility

a) All signaling events are uncorrelated Poisson arrivals

From a cell peak throughput and RRC session density perspective we obtain the following results for the dedicated network optimized for utility:

	UL Traffic Volume [kbps]	UL Traffic Volume [kbps]	UL Traffic Volume [kbps]			DL Traffic Volume [kbps]	DL Traffic Volume [kbps]	DL Traffic Volume [kbps]	
Peak second Traffic	Urban	Suburban	Rural			Urban	Suburban	Rural	
Total offered events / traffic, average / s	25.4	25.2	42.1	kbps		3.1	5.7	11.6	kbps
Total offered events / traffic, peak / s	113.2	79.5	100.6	kbps		13.9	17.9	27.8	kbps
PAER									
LTE air interf. capacity	2989.9	2576.7	1397.2	kbps		5928.2	5395.4	4391.8	kbps
Capacity utilization	**3.79**	**3.08**	**7.20**	%		**0.23**	**0.33**	**0.63**	%

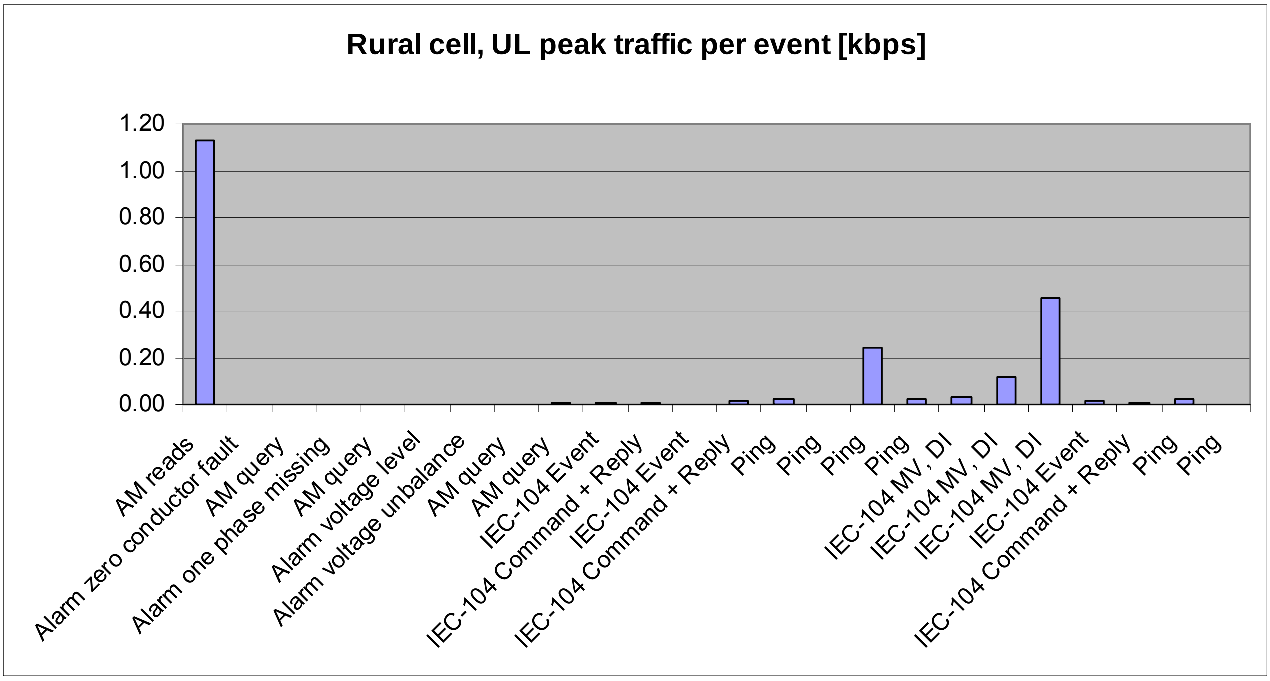
Peak second Traffic	Urban	Suburban	Rural
Peak # of incoming RRC sessions	2	4	17
Existing RRC sessions (RRC_CONNECTED)	1	2	6
Existing RRC sessions (RRC_CONNECTED)	0	4	6
Total of RRC sessions	**3**	**10**	**29**



From a cell peak throughput and RRC session density perspective we obtain the following results for the CSP provided LTE MBB network:

	UL Traffic Volume [kbps]	UL Traffic Volume [kbps]	UL Traffic Volume [kbps]			DL Traffic Volume [kbps]	DL Traffic Volume [kbps]	DL Traffic Volume [kbps]	
Peak second Traffic	Urban	Suburban	Rural			Urban	Suburban	Rural	
Total offered events / traffic, average / s	2.2	2.3	2.1	kbps		0.3	0.7	0.8	kbps
Total offered events / traffic, peak / s	43.1	27.2	9.9	kbps		6.2	8.4	3.8	kbps
PAER									
LTE air interf. capacity	4289.5	3002.1	2568.8	kbps		7383.2	5943.7	5385.2	kbps
Capacity utilization	**1.00**	**0.91**	**0.39**	%		**0.08**	**0.14**	**0.07**	%

Peak second Traffic	Urban	Suburban	Rural
Peak # of incoming RRC sessions	1	1	3
Existing RRC sessions (RRC_CONNECTED)	0	0	1
Existing RRC sessions (RRC_CONNECTED)	0	1	1
Total of RRC sessions	**1**	**2**	**5**

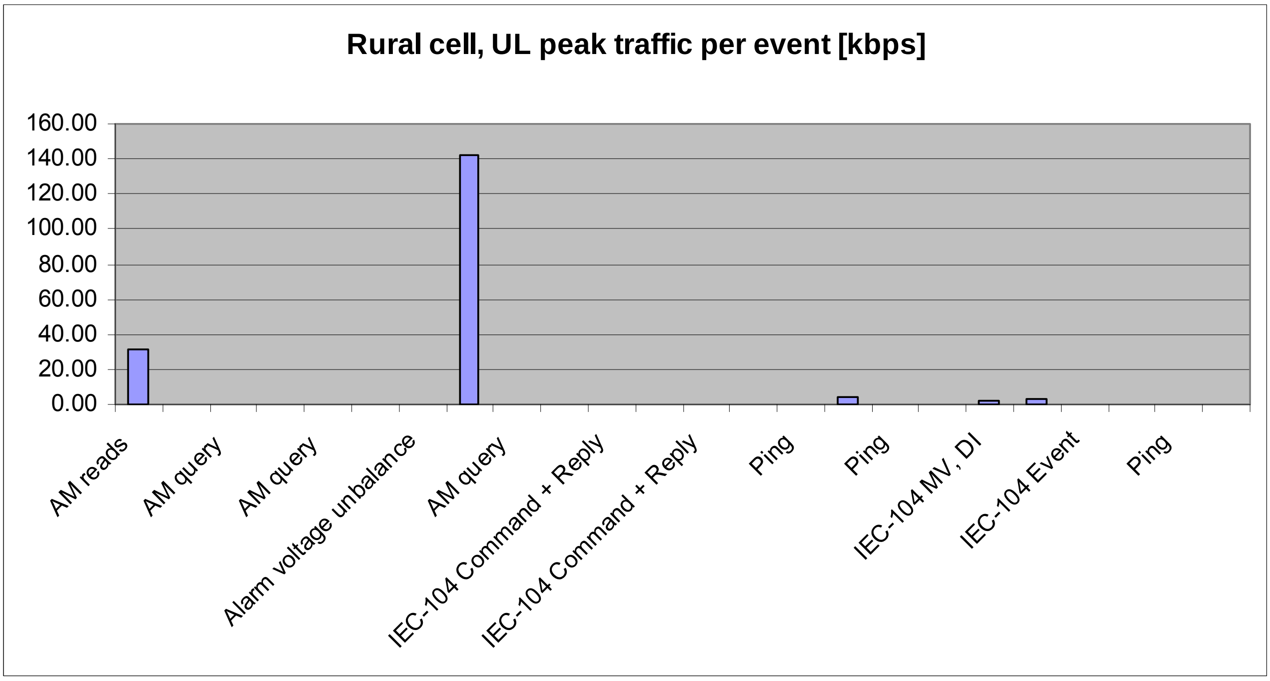


b) Same as a), but then AMR+DMS queries are added into this 'peak second' (6.25% of AMs on a MV feeder are queried)

From a cell peak throughput and RRC session density perspective we obtain the following results for the dedicated network optimized for utility:

	UL Traffic Volume [kbps]	UL Traffic Volume [kbps]	UL Traffic Volume [kbps]			DL Traffic Volume [kbps]	DL Traffic Volume [kbps]	DL Traffic Volume [kbps]	
Peak second Traffic	Urban	Suburban	Rural			Urban	Suburban	Rural	
Total offered events / traffic, average / s	198.4	249.1	184.5	kbps		171.3	223.4	150.1	kbps
Total offered events / traffic, peak / s	261.7	314.7	246.7	kbps		226.0	282.2	200.7	kbps
PAER									
LTE air interf. capacity	2989.9	2576.7	1397.2	kbps		5928.2	5395.4	4391.8	kbps
Capacity utilization	**8.75**	**12.21**	**17.65**	%		**3.81**	**5.23**	**4.57**	%

Peak second Traffic	Urban	Suburban	Rural
Peak # of incoming RRC sessions	2	3	15
Existing RRC sessions (RRC_CONNECTED)	1	2	6
Existing RRC sessions (RRC_CONNECTED)	0	4	6
Worst case event. 6.25% of AM on MV feeder are queried after MV fault.# of queries is Poisson distributed.	27	38	31
Total of RRC sessions	**30**	**47**	**58**



From a cell peak throughput and RRC session density perspective we obtain the following results for the CSP provided LTE MBB network:

	UL Traffic Volume [kbps]	UL Traffic Volume [kbps]	UL Traffic Volume [kbps]			DL Traffic Volume [kbps]	DL Traffic Volume [kbps]	DL Traffic Volume [kbps]	
Peak second Traffic	**Urban**	**Suburban**	**Rural**			**Urban**	**Suburban**	**Rural**	
Total offered events / traffic, average / s	175.2	226.2	144.5	kbps		168.5	218.4	139.3	kbps
Total offered events / traffic, peak / s	230.0	290.6	196.1	kbps		221.2	280.6	189.0	kbps
PAER									
LTE air interf. capacity	4289.5	3002.1	2568.8	kbps		7383.2	5943.7	5385.2	kbps
Capacity utilization	**5.36**	**9.68**	**7.63**	%		**3.00**	**4.72**	**3.51**	%

Peak second Traffic	Urban	Suburban	Rural
Peak # of incoming RRC sessions	1	1	2
Existing RRC sessions (RRC_CONNECTED)	0	0	1
Existing RRC sessions (RRC_CONNECTED)	0	1	1
Worst case event. 6.25% of AM on MV feeder are queried after MV fault.# of queries is Poisson distributed.	27	38	31
Total of RRC sessions	**28**	**40**	**35**

Observations and discussion:

- The impact from the burst of localized AM queries on the cell peak load is quite noticeable. It is the only scenario studied so far in which also the CSP provided LTE MBB network will experience a noticeable load (~10 %);
- Also the 5 MHz LTE dedicated utility network can cope with this momentary peak load (~17.5%);
- When the signaling spikes related to AM queries are considered, the cell capacity utilization does not any longer differ significantly (factor 1.7x) between the two LTE network examples, as the same peak load (due to AM queries) clearly dominates over the rest of the traffic;
- With a LTE eNB supporting up to 400 ... 500 active RRC sessions when more advanced features such as DRX and UE out-of-sync handling are utilized and for the assumed RRC release timer of 5 s, we find that the resulting RRC session densities are quite in line with the air-interface capacity utilization;

From these results it's quite evident that the DMS application (or the related interfaces towards the cellular network APN) has to restrict the possibility to generate burst of localized AM queries. Suitable methods are randomization over time window (as for alarms) and/or location specific scheduling of the queries should the meter locations span several cells.

6 Conclusions

This report contains the distribution system input scenario and the corresponding results from the LTE network dimensioning studies. The scenario is based on selected use cases of the Vattenfall / Finland (VFV) distribution system network which require wireless communications.

Communication requirements have been considered for today's use cases such as AMR, use of AMR alarms and queries in DMS for MV/LV outage management, MV feeder automation and primary substation connectivity.

Average and peak capacity utilization of the LTE core and radio network is analyzed in detail for the selected use cases.

For the considered Distribution Automation (DA) use cases, the calculated traffic is ~2.5 … 4 x smaller than actual measured traffic which is primarily due to missing overheads in managing VPN connections within the model. While this error appears large, it is acceptable for 'order-of-magnitude' estimates and will have little impact on the following conclusions. Significantly more work (measurements / packet analysis from M2M gateway, SCADA and MDMS) would be required to obtain detailed data for better calibration.

Two LTE deployment scenarios were considered:

- a typical CSP provided LTE MBB network;
- a dedicated, sparse LTE network for the utility which is optimized for coverage.

Owing to a better radio link budget and much larger cells the number of required sites for the dedicated utility LTE network is by a factor of 22 lower compared to the CSP provided LTE MBB network: 60 sites instead of 1356 for the considered VFV service area scenario. At the same time, the larger cells are able to pick up a much larger number of meters and RTUs, resulting in higher capacity utilization per cell when compared to the CSP MBB network.

Yet, the overall monthly average and Busy Hour (BH) air interface capacity utilization for the studied VFV scenario is less than ~1 %, and even less so for CSP MBB network.

The aggregate, i.e. from all use cases combined, U-plane peak traffic load on the P-GW is merely in the order of a single DSL connection (~3 Mbps UL, 0.3 Mbps DL). The impact in terms of throughput (3 OM less than typical small P-GW configurations) and TPS (2 OM less) is essentially marginal. Significant are, however, session and context storage requirements which are due to AMR. This traffic characteristics departs significantly from that of MBB devices (smart phones, dongles) and can lead to challenges in economically (down-)scaling of EPC nodes designed for MBB networks when deployed in dedicated utility LTE networks in which SG M2M traffic dominates.

During the worst hour of Sylvi the Fault rate and related IEC-104 alarms and control signaling increased in the time domain by a factor of ~431 compared to the average hour. However, the increase of the total traffic, excluding AMR, during the worst hour of the Sylvi storm is merely 4%. Periodic VPN Pings and regularly sent IEC-104 measured values & digital state indications provide a constant signaling baseload for the DA use cases which masks the storm (fault) induced IEC-104 signaling.

The worst case UL cell peak load in the LTE network for the utility can reach ~7% or even 17.5% if meter queries are not scheduled (or randomized over a time window); the corresponding figures for the CSP MBB network are 1 %, respectively 10%. From these results it's evident that the DMS application has to control and restrict the possibility to generate burst of localized AM queries and alarms.

AMR traffic volumes dominate the total (60%) and give a rise to an overall UL : DL traffic ratio of approximately 2.5 : 1. While it is sometimes argued that LTE TDD has an advantage over FDD in matching asymmetric UL traffic needs, TDD also has a worse radio link budget and hence less cell coverage. This would drive the cost of a dedicated utility LTE TDD network compared to FDD as these networks are strictly coverage limited. Ultimately, however, the potential of dedicated utility LTE networks is driven by spectrum availability.

Based on this case study 2x5 MHz of spectrum would appear as sufficient to operate a dedicated LTE utility and be able to deal also with future SG traffic.

In a revised version of this report during FP3 more speculative SG use cases will be added which could materialize around 2020 such as more advanced distribution automation concepts, retrieving disturbance files from primary substations, video surveillance, etc

7 Abbreviations

OM	Order-of-magnitude

8 References

[1] D4.1.4.3: Optimal Concepts for Smart Grid Communication, SGEM FP1, H. Elias & P. Muszynski, http://research.cleen.fi/research/images/e/e2/RTENOTITLESGEM_D4143_v2.pdf

[2] Holma, Toskala: LTE for UMTS - OFDMA and SC-FDMA Based Radio Access, Wiley, http://onlinelibrary.wiley.com/book/10.1002/9780470745489

[3] Options for a Harmonised Allocation to Support Utility Operations (Smart Grids), Final Report, Study for European Utilities Telecom Council (EUTC) by Aegis

[4] NIST Priority Action Plan 2, Guidelines for Assessing Wireless Standards for Smart Grid Applications, NISTIR 7761, http://collaborate.nist.gov/twiki-sggrid/pub/SmartGrid/PAP02Wireless/NISTIR7761.pdf

[5] SG Network System Requirements Specification v5.0, http://osgug.ucaiug.org/UtiliComm/Shared%20Documents/SG-NET%20PAP%20work-in-progress/Rqmt-Table-wip/SG%20Network%20System%20Requirements%20Specification%20v5.0.xls

[6] "Assessing how to Utilise AMM Comprehensively in the Processes of a Distribution Company", ADINE Seminar and Workshop 17.2.2010 Tampere, Sauli Antila, Vattenfall

[7] "AMR in Outage Management", Cleen Summit 7.4.2011 Wanha Satama, Santtu Vähäkuopus, Vattenfall Nordic Distribution,

[8] "Vattenfall Verkon ja Teklan yhteistyö", Tekla Capital Markets Day, 19.5.2009, Jorma Myllymäki, Vattenfall Verkko Oy

[9] "Jakeluverkko myrskyn silmässä", Käyttövarmuuspäivä 2.12.2010, Jorma Myllymäki, Vattenfall Verkko Oy, http://www.fingrid.fi/attachments/fi/media/Seminaarit/kayttovarmuus_2010/jakeluverkko_myrskyn_silmassa_jorma_myllymaki.pdf

[10] Kesän 2010 myrskyt sähköverkon kannalta, Dnro 306/401/2011, Energiamarkkinavirasto

[11] Energiateollisuus: KESKEYTYSTILASTO 2010, http://www.energiamarkkinavirasto.fi/files/Kes%C3%A4n%202010%20myrsky%20raportti_lopullinen%20_2_.pdf

[12] "USEFULNESS OF AMR DATA IN THE NETWORK OPERATION", LAURA KERÄNEN, MSc Thesis, TUT 2009, http://webhotel2.tut.fi/units/set/opetus/pdf%20julkiset%20dtyot/Keranen_Laura_julk.pdf

[13] "AUTOMATIC METER READING COMMUNICATION AND POSSIBILITIES IN DISTRIBUTION AUTOMATION", Ville Salonen, MSc Thesis, HUT 2007

[14] „Iskraemeco AMR System für Haushalt", August 2007, ISKRAEMEKO

[15] "AMM System General information", Stanislav Miklavčič, ISKRAEMEKO

[16] „Zuverlässige Technologien für effiziente AMM Systeme", Ivan Kern, ISKRAEMEKO

[17] Viola Systems: CASE VATTENFALL: AUTOMATING THE DISTRIBUTION NETWORK http://www.automation.com/pdf_articles/Vattenfall_Viola.pdf

[18] D6.1.1: "Consolidated communication requirement descriptions", SGEM FP2, P. Muszynski, http://research.cleen.fi/research/images/2/2e/SGEM_FP2_D6.1.1_V1.0.doc

[19] NEW BUSINESS AND PROCESS DEVELOPMENT OPPORTUNITIES UTILIZING METER DATA MANAGEMENT SYSTEM, PEKKA MÄKELÄ, MSc Thesis, TUT 2011, http://webhotel2.tut.fi/units/set/opetus/pdf%20julkiset%20dtyot/Makela_Pekka_julk.pdf

[20] Lakervi, Partanen: Sähkönjakelutekniikka, OTATIETO / YLIOPISTOKUSTANNUS 2008

[21] VTT TIEDOTTEITA: Verkkovisio 2030, Jakelu- ja alueverkkojen teknologiavisio http://www.vtt.fi/inf/pdf/tiedotteet/2006/T2361.pdf

[22] @450-verkko, http://www.datame.fi/index.php?id=14

[23] L.E. Bråten, T. Tjelta , "Semi-Markov multistate modeling of the land mobile propagation channel for geostationary satellites". IEEE Transactions on Antennas and Propagation, Vol. 50, No. 12, Dec 2002, pages 1795-1802.

[24] Fernando Pérez Fontán et al. , "An enhanced Markov chain based model for the narrowband LMS channel in built-up areas". International Journal of Satellite Communications and Networking, Vol. 23, No. 2, Mar 2005, pages 111-128.