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Stability Analysis and Performance Comparison of Five 6to4 Relay Implementations

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***Abstract*—Even though the present form of IPv6 has been existing since 1998, the adoption of the new protocol has been very slow until recently. To help the adoption of the IPv6 protocol, several transition technologies were introduced. The 6to4 protocol is one of them, and it can be used when an IPv6 enabled host resides in an IPv4 only environment and needs to communicate with other hosts in such circumstances or with native IPv6 hosts. Five open source 6to4 relay implementations were investigated: Debian Linux – sit, Debian Linux – v4tunnel, OpenWrt – sit, FreeBSD – stf, NetBSD – stf. The measurement method is fully described including our measurement scripts and the results of the measurements are disclosed in detail. The measurements have shown that there are major differences between the different types of implementations.**

***Index Terms*—6to4 relay, IPv6 transition, network communication, performance evaluation, stability analysis**

I. Introduction

FOR more than two decades it is a known fact, that the size of the IPv4 address space is insufficient [1-2]. The lack of the IP addresses withholds the spread of the Internet and causes social and economic damage.

To prevent the IP address exhaustion, a new version of the Internet Protocol, IPv6 has been developed. IPv6 was standardized in 1998 and published in RFC 2460 [3], but it has not been widespread adopted. According to the statistics, less than 8% of the total amount of the traffic reached the Google servers used IPv6 protocol in December 10, 2015 [4]. Several tools and solutions have been developed to slow down the process of the address exhaustion. The Dynamic IPv4 allocation [5], the Classless Inter-Domain Routing (CIDR) [6], the Network Address Translation (NAT) [7], the Carrier-grade NAT (also called NAT444) [8], different type of proxies or Application Level Gateways (ALG), new policies of the IPv4 address transfers [9] successfully delayed the problems generated by the IP address exhaustion, but all of them generated other problems [5].

Three of the five Regional Internet Registries (RIR) already run out of their IPv4 address spaces [10]. The five RIRs have only 5.2 /8 ranges in total, whereas the IANA does not have more address space to assign to the five RIRs since 3 February 2011 [11]. The RIRs work according to strict policies and for a service provider, it is a harder task than ever to get IPv4 address spaces. The speed up of the transition to the new protocol is inevitable. Several IPv6 transition techniques have been developed, which can help the process in different phases of the adoption of the new protocol on the Internet.

There are different situations to solve during the coexistence of the two versions of the IP protocol in the different phases of the transition process:

In theory, the best solution is the Dual Stack (DS) transition method [12], but with the requirements that the two communicating hosts and the network between them have to support a common version of the IP protocol, and because of the IPv4 exhaustion, there is not enough IPv4 address to use this solution. The communicating hosts need both version of the IP addresses and it is almost impossible to provide enough public IPv4 addresses for the clients. Thus, even though it could have been the best solution, now it is too late for using DS as an IPv6 transition method.

In a situation where an IPv6 only client computer needs to communicate with an IPv4 only server, the DNS64 [13] and NAT64 [14] combination is a good solution. The performance, the stability and the application compatibility of some open source implementations of DNS64/NAT64 are examined and proved in [15-17].

If two IPv6 enabled hosts need to communicate with each other over an IPv4 network, they can use different tunneling methods. The 6in4 (also called manual tunnel) [18] with tunnel brokers [19-20], 6rd [21], Teredo [22] ISATAP [23] and 6to4 [24] have different requirements, benefits and drawbacks.

The above list is not exhaustive and a good survey of the different transition techniques can be found in [25].

In this paper, we deal with the 6to4 IPv6 transition solution. The remainder of this paper is organized as follows: first, some properties of the 6to4 transition technique are introduced, second, a short survey of the results of the most current publications is given, third, the selected 6to4 relay implementations are introduced, fourth, our test environment is described, fifth, the performance measurement method of the different implementations is detailed, sixth, the results are presented and discussed, seventh, the comparison of our results is presented, finally, our conclusions are given.

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II. The 6to4 Transition Technique

The 6to4 transition technique uses automatic tunnels, encapsulates the IPv6 packets into IPv4 packets (using protocol number 41, as the configured IPv6 over IPv4 tunnel [26]) [24]. The main advantage of the automatic tunneling is the unnecessity of the manual configuration of the endpoint address of the tunnel. Automatic IPv6-over-IPv4 tunneling determines the IPv4 tunnel endpoint address from the IPv4 address embedded in the destination address of the IPv6 packet being tunneled. 6to4 protocol uses the reserved 2002::/16 6to4 prefix to determine if a 6to4 tunnel creation is necessary [27]. A 6to4 address is an IPv6 address constructed using a 6to4 prefix. The first 16 bits of the 6to4 address contain the 2002 hexadecimal value, whereas the next 32 bits contain the IPv4 address of the 6to4 tunnel endpoint. The next 16 bits can be used to create subnets, and the final 64 bits of the 6to4 address contain the interface ID.

A 6to4 router is an IPv6 router supporting a 6to4 pseudo-interface. It is normally the border router between an IPv6 site and a wide-area IPv4 network, whereas the 6to4 pseudo-interface is the point of the encapsulation of IPv6 packets in IPv4 packets (with other words: the tunnel end-point) [24]. If a 6to4 host has to communicate with a non 6to4 host (for example: native IPv6, Teredo) it needs to use a 6to4 relay router.

Several operating systems can work as a 6to4 router or 6to4 relay router, but for the correct operation, the 6to4 routers and relay routers need public IPv4 addresses.

A 6to4 relay router can be private or public. Public 6to4 relays use the 192.88.99.1 anycast address [28] from the 192.88.99.0/24 6to4 Relay anycast address range [29]. An estimation of the 6to4 relay routers published in 2006 [30]. According to the publication, 8 autonomous systems (AS-es) advertised the 192.88.99.0/24, whereas 6 AS-es advertised the 2002::/16 networks. At the end of the year 2014 these values were 14 and 11, according to the RIPEstat database [31].

It is a good practice, if an Internet Service Provider (ISP) provides a 6to4 relay for its customers in addition to other transition solutions. In this case the relay does not have to be public, and it can use the well-known anycast address, or a network specific address.

Though some security weaknesses are known of the 6to4 transition technique [32], its advantage is that it helps the implementation of the IPv6 protocol without the cooperation of the ISP. This is the reason why we insist that 6to4 is still indispensable in several countries including Hungary. Although 6rd [33] eliminated some of the weaknesses of 6to4, the price of the improvements was that 6rd can only be implemented by the ISPs, and it cannot be used without the cooperation of the ISP of the user at all. We note that the second author of the RFC defining 6rd [33] recommended to move 6to4 to historic status in 2011 [34] and his efforts were only partially successful after several years because not 6to4 itself, but only the anycast prefix for 6to4 relay routers was deprecated in 2015 [35]. Whereas this seems to be a good decision considering the rapid deployment of IPv6 in certain countries (e.g. USA, China), we contend that it was done way too early considering the slow deployment of IPv6 in some other countries including Hungary, too. Despite the depletion of the public IPv4 address pool, the most ISPs in Hungary are rather reluctant to step forward towards IPv6. (What is even worse, it became a common practice that ISPs take away the public IPv4 address from their customers, and give private ones instead. The average user is OK with using CGN, and those who do not like it, will get back a public IPv4 address.) Thus an average countryside home user (one residing not in Budapest) is not able to get IPv6 Internet access. How can this user get access to the IPv6 Internet? We see the following possibilities:

- Use an explicit tunnel with a tunnel broker, however it requires registration and configuration.
- Use 6to4, which is a kind of automatic tunnel and is supported by several operating systems and SOHO routers and thus the user can access IPv6 only sites without any effort.
- Use Teredo as last resort. (But it is intended to be used as a last resort only.)

We agree that 6to4 is not a good solution, but as there is no real replacement, we consider it is still to be kept as working in those areas where the IPv6 deployment is still in its infancy and there is no other way for the clients to reach IPv6 internet without tunnel registration and explicit configuration. Therefore the performance analysis of 6to4 relays is still interesting for those network administrators who are willing to help these clients. We note that dimensioning a 6to4 relay is not an easy task because it is hard to predict where the return traffic will cross the border of the IPv6 Internet and IPv4 Internet. This is why it is crucial to have information about the performance and stability of different free software 6to4 relay implementations.

We also admit that many users of 6to4 may experience operational problems. Section 3 of RFC 6343 [36] mentions measurements reporting high TCP connection failure rate. There are 9 possible reasons were identified. We mention only two of them: e.g. firewalls may filter out protocol number 41, or some ISP may advertise 192.88.99.0/24 but not forward 6to4 traffic for “alien” networks, etc. Section 4 provides appropriate guidelines for vendors, network operators, and ISPs to eliminate the particular issues. Thus 6to4 may be used if all parties take enough care. Unfortunately, the communication of two computers may fail due to the malpractice of a third party because of asymmetric routing.

More details of the operation of the 6to4 technique can be found in the publication [37], and in the related RFCs ([24], [29] and [32]).

III. A Short Survey of Current Research Results

There are a lot of publications about IPv6 and several of them related to the transition to the IPv6 protocol.

There is a very good survey about the state of IPv6 adoption with measurement methods in [38]. The authors of the article used excellent methods for the survey, but the data in it is a little outdated today. A newer, and also very good survey can

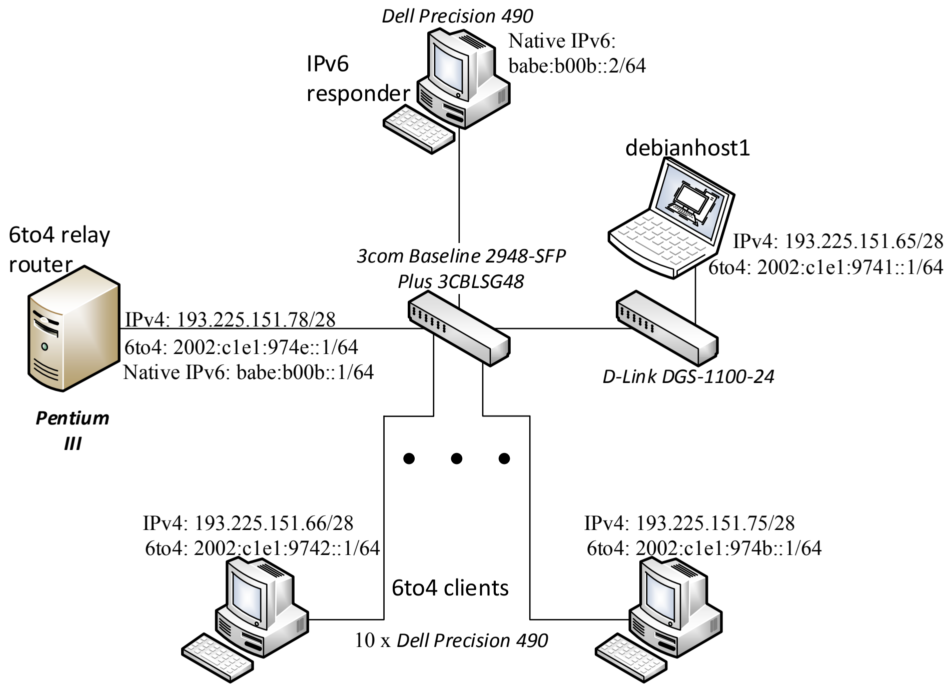

Fig. 1. Topology of the test network.

be found in [39]. The two papers give a good overview about the progress of the transition process.

There are several publications about comparison of different tunneling based transition methods.

In [40] the performance of both the ISATAP and the 6to4 tunneling solution is compared on a Windows XP and Windows Server 2003 based test-bed network. The authors used UDP streaming and ICMP to measure and compare the throughput, the End to End Delay (E2ED), the jitter and the Round Trip Time (RTT) performance characteristics. The final conclusion found the ISATAP protocol significantly more efficient.

Sans and Gamess carried out a performance comparison of the native IPv6 protocol and the following tunneling methods: ISATAP, 6to4, 6rd and Teredo on a test network was built on Linux computers and different numbers of Cisco routers [41]. The authors tested the throughput and the RTT with UDP and TCP protocol both on Ethernet and fast Ethernet network. They concluded, the best choice is native IPv6 but if native IPv6 cannot be used, ISATAP, 6to4, and 6rd are good possibilities. Selecting one tunneling technology over the other depends on many factors. Teredo was presented as the less good solution, whereas, Teredo is the only choice when the hosts to be connected are using private IPv4 addresses and are helped by a NAT server to reach the Internet.

Shah and Parvez performed simulations about the performance of native IPv6, dual stack, 6in4 and 6to4 [42]. The authors used OPNET Modeler (now Riverbed Modeler [43]) to investigate the TCP delay, throughput and response time of the different methods. Naturally, the native IPv6 produced the best results, whereas the second one was the 6to4.

There is a good comparison of the performance of the Windows Server 2008 and 2012 6to4 and 6in4 tunnels in [44]. The authors used UDP and TCP and three games to compare the throughput, the jitter and the delay of the two tunneling methods, but they did not collect data about the resource usage on the computers.

The comparison of the TCP and UDP throughput, RTT, and tunneling overhead with native IPv4, native IPv6 and 6to4 tunneling can be found in [45]. The authors concluded that the 6to4 tunneling mechanism is a suitable method in the early part of the transition period.

The characteristics of the tunneled IPv6 traffic on the border of the Czech national research and education network (CESNET) were investigated in [46], whereas the traffic of the FUNET operated public 6to4 relay was analyzed in [47].

Narayan and Tauch investigated the 6to4 and configured tunnel performance characteristics on two different Linux and Windows operating system [44-46] in a test network.

The performance characteristics of Linux sit, FreeBSD stf, and NetBSD stf based 6to4 relay implementations were investigated in [37].

The performance of and stability of Debian Linux sit, OpenWRT sit and FreeBSD stf were analyzed in our conference paper [51], which is now extended by Debian Linux v4tunnel and NetBSD stf.

IV. TESTED IMPLEMENTATIONS

The following widely used open source [52] (also called free software [53]) operating systems and their 6to4 implementations were chosen for the tests: Debian Linux sit and v4tunnel [54], OpenBSD gif interface [55], FreeBSD stf interface [56], NetBSD stf interface [57], OpenWRT 6to4 plus kmod-sit packages [58]. The open source software can be freely used by anyone, and their licenses allow the performance benchmarks. These two arguments were the most important ones in our selection of the implementations for testing.

The following software versions were used:

- Debian 7.1.0_x86 – sit
- Debian 7.1.0_x86 – v4tunnel
- OpenWRT (Attitude Adjustment) 12.09_x86 – sit
- FreeBSD 9.1_x86 – stf
- NetBSD 6.1.2_x86 – stf

It was found during the preliminary tests that the OpenBSD system does not support the 6to4 transition mechanism.

V. TEST ENVIRONMENT

A. Topology of the network

An isolated test network was built for the performance and the stability measurements. The topology of the network can be seen in Fig. 1. Due to the isolation, any IPv4 and IPv6 addresses could be used on the network. The computer on the top of the figure played the role of the “internet” and responded all of the queries, and the queries were generated by the 10 client computers which can be seen on the bottom of the figure. These computers played the role of the large number of the clients. The clients sent their queries by 6to4 through the 6to4 relay router to the “internet” computer. These queries were generated different levels of load on the 6to4 relay computer during the measurement process. The load was tuned by the number of the active clients. The laptop and the connecting switch on the right side of the figure were used to control the experiments.

B. Hardware configurations

1000Base-TX connections were used on all of the network segments.

A specially low performance computer was built for the 6to4 relay computer so that the client computers could produce high enough load for overloading it. The main goal of the measurements was the comparison of the different implementations and not any hardware related investigation.

The configuration of the 6to4 relay computer was:

- Intel D815EE2U motherboard
- 800MHz Intel Pentium III (Coppermine) processor
- 128MB, 100MHz SDRAM
- Two TP-LINK TG-3269 REV 3.0 Gigabit PCI Ethernet NICs

All of the ten clients and the responder computer were Dell Precision 490 workstations with same configuration:

- DELL 0GU083 motherboard with Intel 5000X chip-set
- Two Intel Xeon 5140 2.33GHz dual core processors (in the responder: Intel Xeon 5160 3GHz)
- 4x1GB 533MHz DDR2 SDRAM (accessed quad channel)
- Broadcom NetXtreme BCM5752 Gigabit Ethernet controller (PCI Express)

C. Software configurations

Debian Linux 6.0.7 with 2.6.32-5-amd64 kernel and OpenBSD 5.3 64 bit version were installed on the clients, and the responder, respectively.

On the responder, NAT66 was used to simulate server computers with different IPv6 addresses. The following commands were used in the /etc/pf.conf file on the responder:

```
set timeout interval 2
set limit states 400000
pass in on bge0 inet6 from any to \
    2001:738:2c01:8000::/64 rdr-to babe:b00b::2
```

All of the client computers used sit or stf interfaces with the following setting in the /etc/network/interfaces file:

```
auto sit0
iface sit0 inet6 static
address 2002:c1e1:9742::1- …974b::1
netmask 64
gateway ::193.225.151.78
```

VI. MEASUREMENT METHOD

The load was generated by `ping6` commands with the following Bash shell script:

```
#!/bin/bash
i=`cat /etc/hostname | grep -o '[0-9]'`
for b in {0..255}
do
  rm -rf $b
  mkdir $b
  for c in {0..252..4}
  do
    ping6 2001:738:2c01:8000::193.$i.$b.$c \
      -c8 -i0 >> $b/6to4-193-$i-$b-$c &
    ping6 2001:738:2c01:8000::193.$i.$b.$c \
      -c8 -i0 >> $b/6to4-193-$i-$b-$c &
    ping6 2001:738:2c01:8000::193.$i.$b.$((c+1)) \
      -c8 -i0 >> $b/6to4-193-$i-$b-$((c+1)) &
    ping6 2001:738:2c01:8000::193.$i.$b.$((c+1)) \
      -c8 -i0 >> $b/6to4-193-$i-$b-$((c+1)) &
    ping6 2001:738:2c01:8000::193.$i.$b.$((c+2)) \
      -c8 -i0 >> $b/6to4-193-$i-$b-$((c+2)) &
    ping6 2001:738:2c01:8000::193.$i.$b.$((c+2)) \
      -c8 -i0 >> $b/6to4-193-$i-$b-$((c+2)) &
    ping6 2001:738:2c01:8000::193.$i.$b.$((c+3)) \
      -c8 -i0 >> $b/6to4-193-$i-$b-$((c+3)) &
    ping6 2001:738:2c01:8000::193.$i.$b.$((c+3)) \
      -c8 -i0 >> $b/6to4-193-$i-$b-$((c+3))
  done
done
```

During the preliminary measurements, the script was tuned to generate about 100% load on the CPU of the 6to4 relay computer with 10 clients.

The variable `i` contains the serial number of the actual client. The script contains two nested `for` cycles. The outer cycle with variable `b` from 0 to 255 runs 256 times, while the inner cycle with variable `c` from 0 to 252 (with stepping interval 4) runs 64 times. The core of the script contains 4 pairs of concurrent `ping6` commands. Each pair of them send out 8 ICMPv6 echo requests with almost zero interval, in parallel, whereas the first 7 of them are started asynchronously with the `&` parameter. The last `ping6` command at the end of the cycle is started normally thus the cycle waits for the execution of it. In a measurement, one client sends out 256*64*8*8= 1048576 ICMP echo requests in total to 256*64*4= 65536 different IP addresses.

In the series of measurements, the number of the clients was increased from one to ten. On the 6to4 relay computer, the `vmstat` command was used to log the CPU and memory consumption. For proper operation of the `vmstat`, -10 nice value was used.

We note that having no timeout specified, the ping command waited two RTTs and then it considered the missing replies as lost. As the RTTs were small, our packet loss rate can be considered as an upper bound of rate of the ultimately lost packets.

VII. MEASUREMENT RESULTS

The results are presented in similar tables for all the tested 6to4 implementations. A detailed explanation is given for the first table only – the others are to be interpreted in the same way.

A. *Debian 7.1.0_x86 – sit*

The results have been listed in Table I. The first row shows the number of clients that executed the test script at the same time. The potential load on the 6to4 relay was proportional with the number of the clients, but the actual number of the packets was less than that, because the measurement script does not start a new iteration until the 8th ping6 command is finished. The second row contains the packet loss ratio. Rows 3, 4 and 5 show the average, the standard deviation and the maximum value of the response time, respectively. The average and the standard deviation of the CPU utilization of the 6to4 relay computer are shown in the Rows 6 and 7. Row 8 contains the memory consumption of the 6to4 process on the relay computer. (This parameter can be measured with high uncertainty, because its value is very low and other processes than the 6to4 relay implementation may also influence the size of the used memory of the computer.) The last row shows the number of forwarded packets per seconds.

The graphical representation of the forwarded packets per second and the CPU utilization are shown in Fig. 2.

Evaluation of the results:

Despite the fact that packet loss occurred in all cases, the proportion of it was always very low and it increased with more clients. (The maximum value of it was 0.061% with ten clients, which means about 6 packets from 10.000 packets were lost.)

The average, the standard deviation and the maximum value of the response times were increasing with higher load on the 6to4 relay computer, but the average value did not exceed 1.63 milliseconds with ten clients.

The CPU utilization were increasing continuously, but not linearly.

The deviation of the CPU utilization were higher with 4, 5, 6 and 7 clients than with other number of clients, which

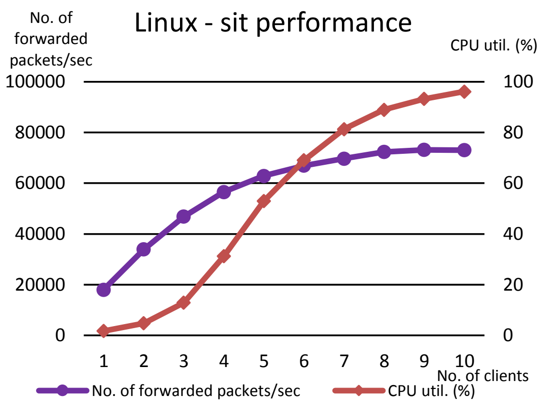

Fig. 2. Linux sit forwarded packets and CPU utilization.

TABLE I
DEBIAN LINUX – SIT 6TO4 RELAY PERFORMANCE RESULTS

Number of clients		1	2	3	4	5	6	7	8	9	10
Packet loss (%)		0.002	0.006	0.008	0.013	0.020	0.035	0.035	0.037	0.048	0.061
Response time (ms)	Average	0.287	0.353	0.445	0.566	0.710	0.868	1.043	1.209	1.411	1.626
	Std. dev.	0.174	0.248	0.353	0.423	0.509	0.588	0.685	0.722	0.832	0.864
	Maximum	27.900	28.400	28.500	28.900	29.400	30.700	31.100	34.100	32.800	39.600
CPU Utilization (%)	Average	1.756	4.821	12.933	31.243	52.964	69.049	81.319	88.941	93.206	96.132
	Std. dev.	1.944	2.811	5.619	12.215	16.379	16.493	12.690	9.817	5.289	7.388
Memory consumption (kB)		10.855	10.418	10.363	10.594	10.824	10.996	10.855	10.994	10.828	11.137
Traffic volume (packets/sec)		18051	33953	46856	56534	62853	66947	69663	72304	73129	73050

TABLE II
DEBIAN LINUX – V4TUNNEL 6TO4 RELAY PERFORMANCE RESULTS

Number of clients		1	2	3	4	5	6	7	8	9	10
Packet loss (%)		0.003	0.006	0.008	0.011	0.018	0.033	0.036	0.039	0.047	0.060
Response time (ms)	Average	0.287	0.351	0.444	0.579	0.709	0.865	1.007	1.198	1.389	1.632
	Std. dev.	0.174	0.251	0.334	0.428	0.508	0.588	0.690	0.776	0.842	0.887
	Maximum	27.800	27.700	28.700	29.920	24.000	30.100	31.300	35.100	33.900	32.800
CPU Utilization (%)	Average	1.915	4.886	14.202	30.927	51.121	69.555	80.392	89.042	93.441	96.444
	Std. dev.	1.727	3.037	6.871	12.412	16.664	14.790	13.807	10.084	7.934	5.461
Memory consumption (kB)		10.664	10.559	10.910	10.555	10.855	10.728	10.730	10.602	11.102	11.438
Traffic volume (packets/sec)		18083	34062	47079	55828	62788	67181	71315	72759	74025	72792

indicates some fluctuation in the utilization.

The memory consumption was almost constant and very low, and the maximum value of it was 11.14kB with ten clients.

The traffic volume increased until the system reached its limit with 9 clients. With 10 clients, the number of transferred packets were slightly decreased from 73129 to 73050.

B. Debian 7.1.0_x86 – v4tunnel

The results have been listed in Table II, whereas the graphical representation of the forwarded packets per second and the CPU utilization are shown in Fig. 3.

Evaluation of the results:

The packet loss ratio was always very low and it strictly increased with the number of clients.

The average and the standard deviation value of the response times were increasing with higher load on the 6to4 relay computer, and the average value reached its maximum value with ten clients (1.632 ms).

The CPU utilization were increasing continuously, but not linearly.

The standard deviation of the CPU utilization were higher with 4, 5, 6 and 7 clients than with other number of clients, which indicates some fluctuation in the utilization.

The memory consumption was almost constant and very low, and the maximum value of it was 11.44kB with ten clients.

The traffic volume increased until the system reached its limit with 9 clients. With 10 clients, the number of transferred packets were decreased from 74025 to 72792.

C. OpenWRT (Attitude Adjustment) 12.09_x86 – sit

The results have been listed in Table III., whereas the graphical representation of the forwarded packets per second and the CPU utilization are shown in Fig. 4.

Evaluation of the results:

The packet loss ratio was always very low and it strictly increased with the number of clients. The maximum value of it was 0.089% with ten clients.

The average and the standard deviation value of the response times were increasing with higher load on the 6to4 relay computer, but the average value did not exceed 2.16 milliseconds with ten clients.

The CPU utilization with two clients was 4.5 times greater

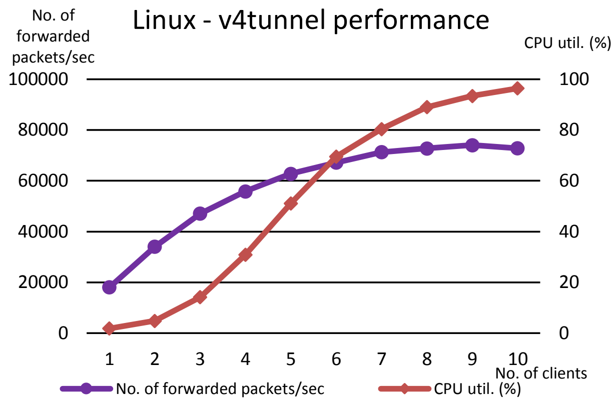

Fig. 3. Linux v4tunnel forwarded packets and CPU utilization.

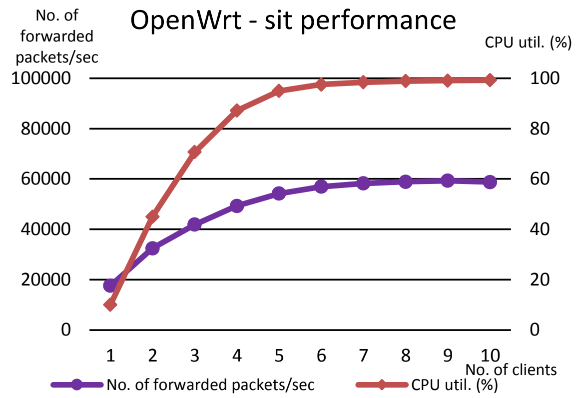

Fig. 4. OpenWrt sit forwarded packets and CPU utilization.

TABLE III
OPENWRT (ATTITUDE ADJUSTMENT) 12.09_X86 – SIT 6TO4 RELAY PERFORMANCE RESULTS

Number of clients		1	2	3	4	5	6	7	8	9	10
Packet loss (%)		0.004	0.006	0.007	0.013	0.018	0.026	0.036	0.064	0.079	0.089
Response time (ms)	Average	0.314	0.402	0.568	0.733	0.909	1.118	1.358	1.616	1.873	2.160
	Std. dev.	0.161	0.239	0.330	0.420	0.508	0.583	0.652	0.705	0.773	0.829
	Maximum	25.000	25.300	25.500	25.500	26.500	27.100	27.000	27.100	27.300	28.100
CPU Utilization (%)	Average	10.067	45.015	70.713	87.188	94.979	97.540	98.467	98.916	99.066	99.288
	Std. dev.	3.188	5.593	5.828	9.376	7.954	7.462	4.991	4.567	4.824	4.410
Memory consumption (kB)		10.316	10.414	10.359	10.727	10.469	10.324	10.746	10.492	10.066	10.469
Traffic volume (packets/sec)		17595	32488	41906	49270	54196	56920	58272	58928	59332	58763

TABLE IV
FREEBSD 9.1_X86 – STF 6TO4 RELAY PERFORMANCE RESULTS

Number of clients		1	2	3	4	5	6	7	8	9	10
Packet loss (%)		0.013	0.008	0.010	0.012	0.013	0.015	0.017	0.018	0.019	0.019
Response time (ms)	Average	0.315	0.456	0.681	0.941	1.268	1.637	2.011	2.385	2.740	3.126
	Std. dev.	0.111	0.171	0.314	0.404	0.450	0.457	0.463	0.466	0.480	0.490
	Maximum	22.200	9.220	12.800	15.400	17.600	18.100	18.800	18.500	19.600	19.400
CPU Utilization (%)	Average	51.525	77.110	88.994	96.380	98.482	99.435	99.395	99.371	99.462	99.859
	Std. dev.	6.899	5.140	6.465	7.398	7.593	3.447	5.336	6.445	5.971	0.475
Memory consumption (kB)		0.008	0.012	0.012	0.273	0.395	0.398	0.445	0.406	0.500	0.492
Traffic volume (packets/sec)		17594	30656	37613	41982	43681	43892	43875	43819	43970	43737

than the value with one client. Then the slope was reduced, until the CPU approached its maximum capacity with 6 clients.

The standard deviation of the CPU utilization were under 10% in each case, which indicates consistent utilization of the CPU.

The memory consumption was almost constant and very low.

The traffic volume increased until the system reached its limit with 9 clients. With 10 clients, the number of transferred packets were decreased by 0.97% from 59332 to 58763.

D. FreeBSD 9.1_x86 – stf

The results have been listed in Table IV., whereas the graphical representation of the forwarded packets per seconds and the CPU utilization are shown in Fig. 5.

Evaluation of the results:

The packet loss ratio was always very low and starting from two clients it increased with the number of clients, whereas the value of it was the same with one and five clients. The maximum value of it was 0.019% with ten clients.

The average and the standard deviation value of the response times were increasing with higher load on the 6to4 relay computer, but the average value did not exceed 3.13 milliseconds with ten clients. The maximum value of the response times showed some fluctuation

One client could generate 51.53% load on the CPU. The CPU utilization was increasing continuously, but not linearly, until the CPU reached its almost maximum capacity (99.44%) with 6 clients.

The standard deviation of the CPU utilization was under 10% in each case, whereas it was very small (0.46%) with ten clients. This phenomenon indicates consistent utilization of the CPU.

The memory consumption was extremely low and it was growing almost continuously.

The traffic volume increased until the system reached its limit with 6 clients. From this point the throughput of the system started very slightly fluctuating. The maximum value of the number of transferred packets per second was 43970 with 9 clients.

The relay did not show significant decrease in its throughput even in serious overload situations thus it complied with the graceful degradation principles [59].

E. NetBSD 6.1.2_x86 – stf

The results have been listed in Table V., whereas the graphical representation of the forwarded packets per seconds and the CPU utilization are shown in Fig. 6.

Evaluation of the results:

The proportion of the packet loss ratio strictly increased until 5 clients, where it started to decrease monotonically. This phenomenon is strange, but the packet loss ratio was always very low.

The average, the standard deviation and the maximum value of the response times were increasing with some fluctuation, but the average value did not exceed 2.52 milliseconds with ten clients.

One client could generate 38.96% load on the CPU. The CPU utilization was increasing continuously, but only by smaller and smaller value.

The standard deviation of the CPU utilization was under 10% in each case, which indicates consistent utilization of the CPU.

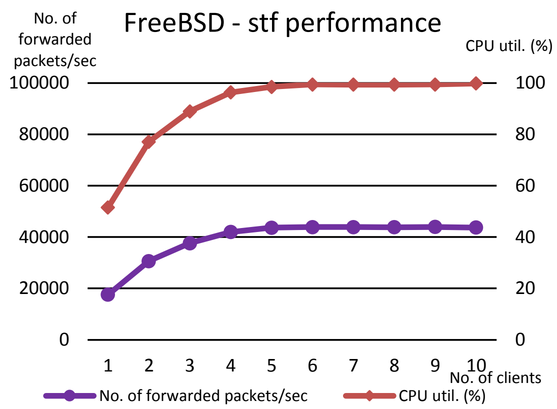

Fig. 5. FreeBSD stf forwarded packets and CPU utilization.

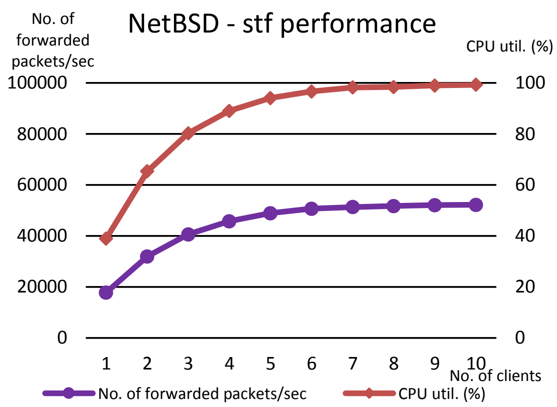

Fig. 6. NetBSD stf forwarded packets and CPU utilization.

TABLE V
NETBSD 6.1.2_X86 – STF 6TO4 RELAY PERFORMANCE RESULTS

Number of clients		1	2	3	4	5	6	7	8	9	10
Packet loss (%)		0.011	0.016	0.028	0.047	0.056	0.051	0.044	0.038	0.031	0.031
Response time (ms)	Average	0.301	0.418	0.603	0.823	1.061	1.326	1.620	1.908	2.210	2.519
	Std. dev.	0.186	0.236	0.319	0.403	0.499	0.571	0.631	0.681	0.707	0.712
	Maximum	5.760	11.500	13.600	16.900	18.900	21.400	21.100	21.700	22.200	24.300
CPU Utilization (%)	Average	38.957	65.382	80.290	89.055	94.130	96.671	98.259	98.435	99.020	99.306
	Std. dev.	4.519	6.229	9.771	3.769	5.878	6.664	3.759	5.751	6.243	4.642
Memory consumption (kB)		0.016	0.027	0.055	0.148	0.191	0.203	0.695	0.336	0.480	0.180
Traffic volume (packets/sec)		17797	31937	40639	45745	48913	50686	51345	51750	52062	52202

The memory consumption was extremely low and it was growing with some fluctuation.

The traffic volume strictly increased.

VIII. Comparison of the Results

To facilitate the comparison of the properties of the different 6to4 relay implementations, we represented the packet loss ratio, the response time, number of forwarded packets per second and the average value of the CPU utilization in graphical form in Figures 7, 8, 9 and 10, respectively.

It is visible at first sight that the Linux sit and v4tunnel produced almost the same results in all of the four represented areas.

All of the tested implementations proved to be reliable and the packet loss ratios of the different implementations were always low. The packet loss ratio of the Linux and OpenWrt implementations increased with the number of clients, whereas the NetBSD stf produced the highest packet loss with 5 clients. We note that even these low packet loss rates may cause significant loss of TCP performance. For example 0.08% packet loss may result in about 50% decrease of TCP performance at 80ms RTT, see the calculations of [60].

All of the implementations proved their stability under overload situations.

Linux v4 tunnel forwarded the most packets per second, but the performance of it started to visibly decrease in overload situation, whereas the Linux sit system only differs slightly. The OpenWrt sit performance is the next one, and the two BSD systems are the last competitors in the performance comparison. FreeBSD stf produced 43970 maximum throughput, whereas Linux v4tunnel had 74025 maximum packets per second. This means Linux outperformed the FreeBSD system by 1.68 times.

All of the implementations use negligibly small amount of memory, which is usually proportional to the generated load.

With one client, all of the implementations forwarded similar number of packets, but with significantly different CPU utilization, which property can explain the high degree of difference in the performance with more clients. Linux sit 6to4 relay implementation used 1.76% of CPU with one client, whereas FreeBSD stf used 51.53%, which means about 29 times difference.

IX. Conclusion

The 6to4 protocol is a useful transition technique in a situation, where two IPv6 enabled hosts have to communicate over an IPv4 only network. All of the tested open source 6to4 relay implementations are reliable solutions in production networks, but the two Linux based ones showed the best

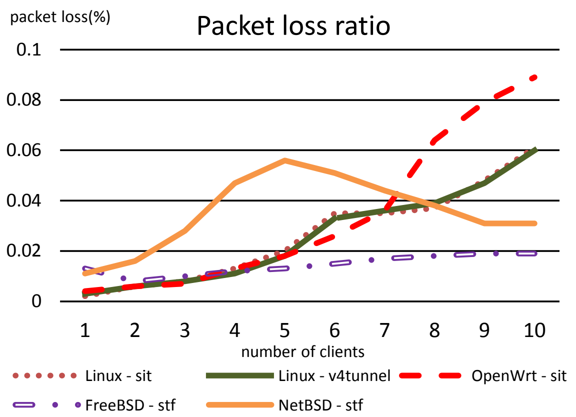

Fig. 7. Packet loss ratio of the different 6to4 implementations.

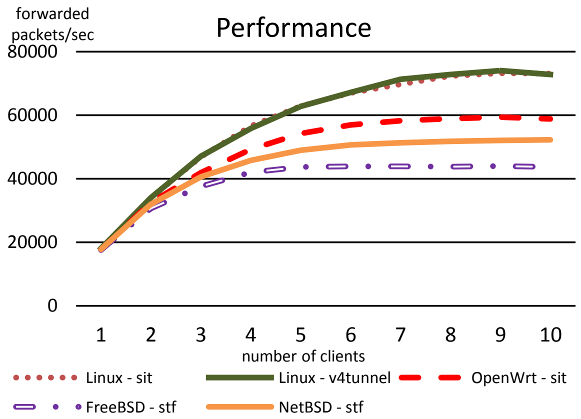

Fig. 9. Performance of the different 6to4 implementations.

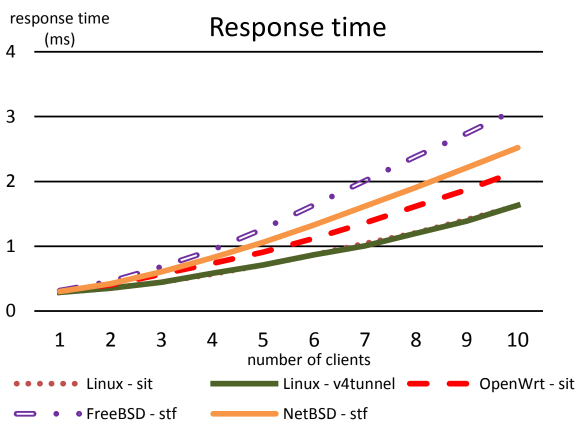

Fig. 8. Response time of the different 6to4 implementations.

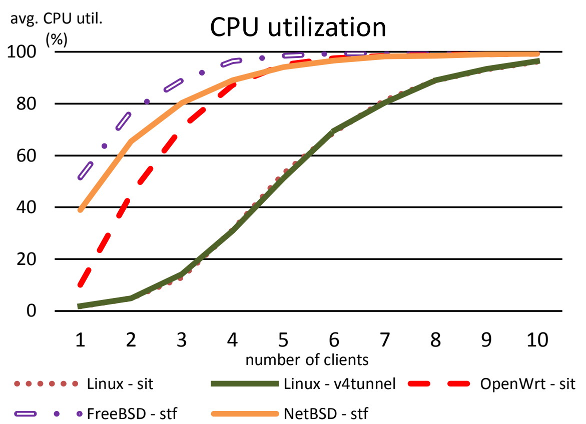

Fig. 10. Average CPU utilization of the different 6to4 implementations.

performance characteristics, whereas the OpenWrt based one was the second to them. In an environment, where BSD systems are preferred, the two BSD based implementations are usable solutions as well.

The authors hope that their work has contributed to the early adoption of the IPv6 protocol and the published results and methodology are valuable for both researchers and network professionals.

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Supporting LTE Network and Service Management through Session Data Record Analysis

Dániel Kozma, Gábor Soós, Pál Varga

Abstract—**Gathering and processing data for performance and fault management continues to be a burning issue, from LTE operations and maintenance point of view. Regarding the Evolved Packet Core (EPC), this is especially true, since it has newly defined interfaces, with new protocols - some of them are even ciphered. Network-wide data capture and analysis for the EPC requires new processing methods. These would allow operators to correlate control and user plane information of various interfaces and protocols. There are many obstacles to overcome here, including ciphered control messages and global identifiers hidden by temporary ones. This paper presents a system for S1AP session data record assembling, it shows what key parameters are needed to be extracted in order to enable expert analysis. The deciphering mechanism is especially important here, hence we discuss how its success affects analysis results. We present Call Data Record assembling methods for various scenarios - such as network attachments or tracking area changes. Furthermore, this paper presents the methods for gathering cross-correlated data on specific fault management use-cases, especially for unsuccessful voice calls.**

I. INTRODUCTION

WIRELESS data traffic is increasing exponentially worldwide [1]. Supporting and managing this growth of traffic on the signaling links poses a great challenge to the operators. Fault management - especially the detection and the root cause analysis of failures - has become very complex, and requires deep telecommunications knowledge. Magyar Telekom - the Hungarian subsidiary of the Deutsche Telekom Group - is facing a milestone in its operation, when introducing voice calls over its 4G network - or in other terms, the Voice over LTE (VoLTE) [2] service. One of the key information-exchange points of 4G call establishment is the S1-MME interface (between eNodeB and MME entities; see Fig. 1). Various important elements of 4G call procedures can be observed at this interface - hence its monitoring is critical from the operator's point of view. On this interface, the role of the S1 Application Protocol (S1AP) [3] is essential when introducing the 4G voice call feature. The monitoring of this interface is important from the Voice over LTE service assurance point of view. Passive monitoring is supposed to be lossless: when the links are tapped, and the probes receive data in a non-intrusive manner, they cannot ask for resending anything. What they missed seeing, they have lost capturing. Based on the monitoring data, engineers can support performance management, network optimization, as well as failure detection, which is one of the most important tasks for operations and maintenance. This paper discusses the requirements and the functions of an S1AP monitoring system, which is under deployment. Furthermore, the paper presents some practical use-cases on call tracing with deciphering issues, as well.

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II. MONITORING THE LTE EVOLVED PACKET CORE

Before discussing the monitoring requirements, this section briefly summarizes the main functions of LTE EPC nodes, and lists the interfaces among them. Parts of LTE network monitoring are discussed in the scientific community; however papers that are sharing actual methodologies and results appear very rarely. The motivations and fundamental challenges of LTE monitoring are discussed in [8]. The basics of network monitoring applied to LTE core system monitoring are summarized in [9]. In [10] the authors describe protocol decoders for LTE, and raise similar issues that our current paper raises and solves.There are also descriptions availale for complete performance management solutions for the backhaul [12] and for end-to-end services [11] – these use the results of LTE EPC monitoring systems, for which an example is presented in the current paper. A CDR synthesis-system for the S1-MME interface is described in [13] – this system shares the fundamentals with the SGA system described in the following sections.

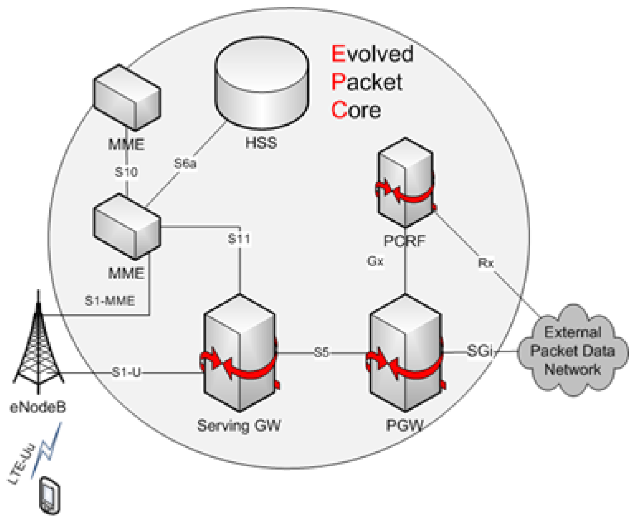

Fig. 1. The architectural elements and interfaces of the LTE EPC

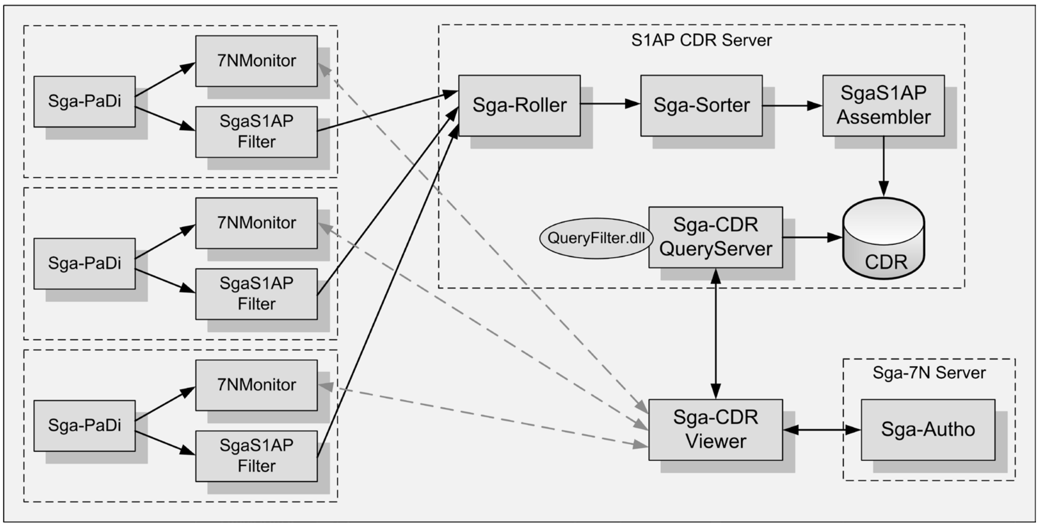

Fig. 2. Monitoring architecture for S1AP CDR creation within the SGA-7N Monitoring System [7]

A. LTE EPC Architecture

The LTE Evolved Packet Core (EPC) [4] comprises merely packet switched network elements; it only supports the legacy circuit switched functions through IP-based packet transfer. Fig. 1 depicts the architecture of the LTE Evolved Packet Core - and the defined interfaces in between its elements.

MME (Mobility Management Entity): The MME lies on the border of the EPC and EUTRAN (Evolved Universal Mobile Telecommunications System Terrestrial Radio Access Network) - and is mainly responsible for mobility-management. Its main functions include controlling handovers between eNodeBs (Evolved NodeB, Base Station), SGW (Serving Gateways) or MMEs, connecting to HSS (Home Subscriber Server), user identification, authentication and controlling the roaming functions. MME registers and handles the User Equipment (UE) in his own area, registers where the UE is located, either exactly at eNodeB level (if communication is active), or within a Tracking Area (TA), which is designated to a group of eNodeBs (in case of passive UE, no active connection is needed).

SGW (Serving Gateway): The SGW is responsible for user traffic stream handling, and controlling the allocation of resource capacities, the changes or deletion of sessions and finishing IP connections. From the eNodeB point of view, it is a fix, anchor node through which the core network elements can be accessed. Furthermore, the SGW controls the User Plane tunnels with GPRS Tunneling Protocol (GTP) [5], although this can be also guided by the MME or the PGW - depending on the process rules.

PGW (Packet Data Network Gateway): PGW can be seen as an edge node of the EPC, since it ensures the connections to external data networks (e.g., the Internet or a private corporate network) and handles the UE's data traffic that is entering or leaving the core network. Besides, it offers interfaces for further functions such as QoS control or billing.

HSS (Home Subscriber Server): HSS takes the roles of HLR/AuC (Home Location Register/Authentication Centre) in the LTE network. It can be seen as the ultimate data storage that contains the subscribers' service-related data. The HSS stores the subscribers' profile, containing the enabled services and access (e.g. allowed roaming services to external networks). It is mainly responsible for access management and authentication, and it also registers the subscribers' position within the network. The HSS cooperates with the MME in all UE-related change events that are administered by the EPC.

PCRF (Policy and Charging Rules Function): Based on its predefined policies and QoS-related rules, the PCRF sends control information to the PGW. This piece of information is called "Policy Control and Charging rules", and it is exchanged between the PCRF and the PGW when a new bearer is set up, e.g. in case new UE activates new PDP to the network or a new UE requires a data plane bearer with a different QoS policy.

B. Monitoring functions

The core network of Magyar Telekom is overseen by the SGA-7N network monitoring system, developed by AITIA International Inc.[6]. The main aim of this monitoring is failure detection and analysis. Further uses include generating key performance indicators on network segments and servicing scenarios, detecting and real-time filtering of fraudulent cases, assembling session- and call-data records for further analysis. The special hardware of the monitoring probes connects to all sorts of network interfaces from E1 to Multi-Gigabit Ethernet, and it also ensures high-precision time-stamping. Lossless traffic capture and real-time data processing and traffic analysis are key features of network monitoring. The connection is passive (non-intrusive), and control-plane traffic is collected bit-by-bit; then, it is stored and pre-processed to allow further analysis. The monitoring system creates signaling statistics, session- and call-data records, allows run real-time call tracing based on the collected data, and enables post-processing for further investigations.

III. Session Data Records of the S1AP Interface

The S1AP-CDR system is part of the SGA-7N monitoring systems. It assembles records from the S1AP traffic, the control messages exchanged between the eNodeBs and MMEs. The architectural view of the functional elements for CDR-creation can be seen in Fig. 2.

When capturing the traffic, the Sga-PaDi (Packet Distributor) on the monitoring probes passes the packets to the SgaS1APFilter module for separating the non-S1AP traffic traversing on the link. The messages are collected by the Roller function, which combines the messages arriving from different monitors. During the next step, the Sorter receives the records where the traffic will be ordered - based on time-stamp. Thanks to the buffer before and after the Sorter, this part can be stopped and started anytime without losing any packets. The chronologically ordered packets are transferred to the Assembler, where S1AP-CDR records get generated. In order to avoid data loss before stopping the Assembler, status saving is required. With this, we can also avoid disturbing transient effects during the restart. The generated S1AP-CDR records then become readable and searchable also.

A. S1AP CDR Assembling

In order to understand the necessities of CDR assembly we have to look into the details of "Filter" and "Assembler".

SgaS1AP Filter: The Filter is aimed to decrease the traffic between the nodes with passing over merely the relevant packets. This module receives traffic from Sga-PaDi, separates Paging and non-Paging messages from the S1AP traffic and generates groups from Paging messages. The filtered S1AP traffic is forwarded to the SgaRoller and logs in .csv format the counters periodically (e.g. every 15 minutes).

SgaS1AP Assembler: This module owns the advanced logic of assembling session data records from individual messages [7]. It selects the processable S1AP messages and associates them with each other, by using their contained identifiers: mme-ue-s1ap-id and enb-ue-s1ap-id. The S1AP connection can be clearly identified between the MME and eNodeB - based on these parameters, within a specific time-range. It associates the S1AP/Paging messages to the connections using the M-TMSI (MME-Temporary Mobile Subscriber Identity). The associated messages are written into records, together with the corresponding IMSI. This latter association comes from the information gathered from the central Key-Servers, which connect ciphering keys and IMSIs from S6a, as well as Gr and Gn interfaces. The internal processes of CDR assembling can be fully traced with the help of internal counters, which are logged and recorded as 15 min records in .csv format.

B. Presentation of S1AP CDRs

The CDR Viewer is the visualization part of the Sga-7N network monitoring system. The database can be searched with different parameters of various protocols, including BSSAP/RANAP, SGsAP, S1AP and GTP. The main features are the following:

- by default only the basic CDR parameters are shown,
- the CDR details appear when clicking on the chosen record,
- presentation can be configured so that it shows or hides various traffic parameters,
- changes can be saved to ASCII TEXT, CSV, RTF and HTML format,
- sophisticated authentication in the hidden attributes.

With the "Get messages" request, the messages that were assembled together for the CDR get shown in a protocol decoder view (which also has a bit-by-bit viewer). This function is provided by the Sga Message Viewer, the ultimate protocol decoder that belongs to the monitoring system.

C. Ciphering issues

During the S1-MME interface monitoring it is very helpful for the operators to be able to search exactly the IMSI and to show all corresponding control messages. To do this we also need to decrypt the encryption on the interface. Currently, commercial 4G voice calls are not supported in the Magyar Telekom network yet, CS fallback is used instead for handling calls. To do this, the UE has to change radio access type to 3G or 2G. This is hard to monitor mainly because the encryption keys are transmitted inside the combo MME-SGSN node. Monitoring the outside interfaces of the Core nodes, GTP, MAP (Mobile Application Part) and DIAMETER messages are received and by saving all IMSI-key exchange, these encryptions can be cleared [7]. The decryption and ordering of different encryptions is a complex problem. To validate the final solution AITIA [7] implemented a specific software tool for manual decryption, that can be used with the help of the proper, saved keys. The software requires the following parameters, based on an "Attach" event [4]:

- CK (Ciphering Key), IK (Integrity Key), AUTN (Authentication Key)
- MCC (Mobile Country Code), MNC (Mobile Network Code): basic network identifiers,
- Based on the identifiers calculating the KASME
- Integrity and ciphering algorithm (based mainly on EIA1/EEA1)
- Input: the file which we want to decrypt
- Output: where we would like to save the results
- check MAC (Medium Access Control) and decode: validation and decoding

To decrypt the TAU (Tracking Area Update) messages we need different parameters, after the IK and CK, NonceMME and NonceUE parameters are also requested (see Fig. 3). Let's examine some cases where is a need to use the encryption keys, and to use the SGA4MD software to find the user records on the S1AP interface [8].

First Example, Basic event

User attaches to the 4G network and the MME requires a key [7].

1, On the HLR-HSS connection SAI (Send Authentication Info) messages originating from the MME should be searched.

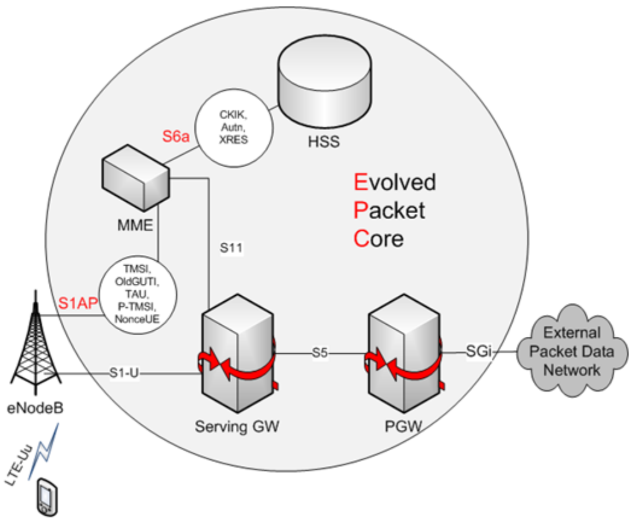

Fig. 3. LTE Authentication and Key Agreement - S1AP and S6a parameters

2, On the S1AP the attached messages should be paired; the easiest way is to search the appropriate XRES (Expected Response) in the ACRS (Accounting Requests) messages.
3, To get the full ACRS, choose the full S1AP dialog.

Second example, Attach case

User connects to 4G, but SGSN-MME receives the key earlier during a 3G attach. In some cases the key cannot be seen because of the combined SGSN-MME node. The original key-exchange can be monitored merely on the SGSN-HLR MAP connection [7].

1, On S1AP, Attach messages should be searched. These contain two kinds of TMSIs (Temporary Mobile Subscriber Identifier). Choose the one in the "Old GUTI"(Globally Unique Temporary ID).
2, Search for this on GTP among the "SGSN Ctxt" and "Identity" messages. For this example, the Identity message should be searched. It is possible that there is no match, again, because of the combined SGSN-MME.
3, Choose the whole S1AP dialogue of the Attach.
4, If there is ACRS among the messages, the new key should be searched (a) in GTP messages, or (b) in the HLR-HSS connection. The authentication vector can be found based on XRES; and the KASME can be calculated.
5, For the first part of the S1AP message exchange the first key, whereas for the last part of the S1AP message exchange the second key should be used.
6, It is not easy to find the original key: the M-TMSI sharing is encrypted on S1AP, hence it cannot be read.
7, In order to decrypt, the GTP search should be based on GTP-TEID filter; the "Create"-s according to IMSI and the search for those TEIDs on the S1AP should be issued.

Third example, Tracking Area case

1, There can be at least two kinds of searches: either (a) "SGSN ctxt transfer" search on GTP, or (b) TAU search on S1AP.
(a) Let's search on the GTP SGSN ctxt transfer to the MME direction. The search is not trivial, because we can see also the 3G-3G change [7]. The solution is to check the MME-SGSN nodes, because they have different IP addresses, so the filtering of the search is simplified.
(b) To filter the search for those TAUs on S1AP, we need such TAUs that have the same NAS Key Set ID.
2, Based on the earlier two cases (a) and (b), we have to search the messages travelling through the other protocol. This time - similarly to the Attach-case - we need the retransformed P-TMSI (Packet-Temporary Mobile Subscriber Identifier) from the Old GUTI.
3, Based on the actual keys seen on the GTP (CK, IK) and the TAU message containing the NonceUE parameter, the KASME key can be derived. In case of Handover, the Sec Mode command message is necessary, because it contains NonceU and NonceMME fields together.

IV. Analysis methods for S1AP CDRs

In some cases, the S1AP CDRs are assembled irregularly; this is marked by the assembler through writing error-messages. These have to be investigated. In order to carry out the investigation, deep knowledge is needed about the network architecture, the S1AP protocol itself, and some experience of the S1AP collecting software's operation. In the following we demonstrate some typically irregular scenarios of the CDR assembly procedure.

Incomplete - Release

Cases belonging here start with "Incomplete" and close with "Release" messages of the S1AP CDR assembling procedure. During the process, we receive packets after the closed connection, which was not included into the CDR#1 - and a new record was opened for CDR#2. The message was received very close in time to the DelayedClosedTimeout, but not exceeding eg. DelayedClosedTimeout = 5s. As an example: a lot of messages were received within 4,947s. After changing DelayedClosedTimeout = 6s, we decreased the number of such irregularities with one magnitude - which is a good result [7].

Incomplete - Error

Further investigating the cases of messages starting with Incomplete, we focused on the CDRs closed with "error". In case of Incomplete-Error CDRs, the CDR#1 completion is prevented by a different CDR, because the eNodeB-MME reference IDs got modified. During the investigation we found, that although the IDs got modified, later we have received messages with the original reference IDs. After modifying the assembling procedure to hold the old IDs for a longer period, the problem was eliminated.

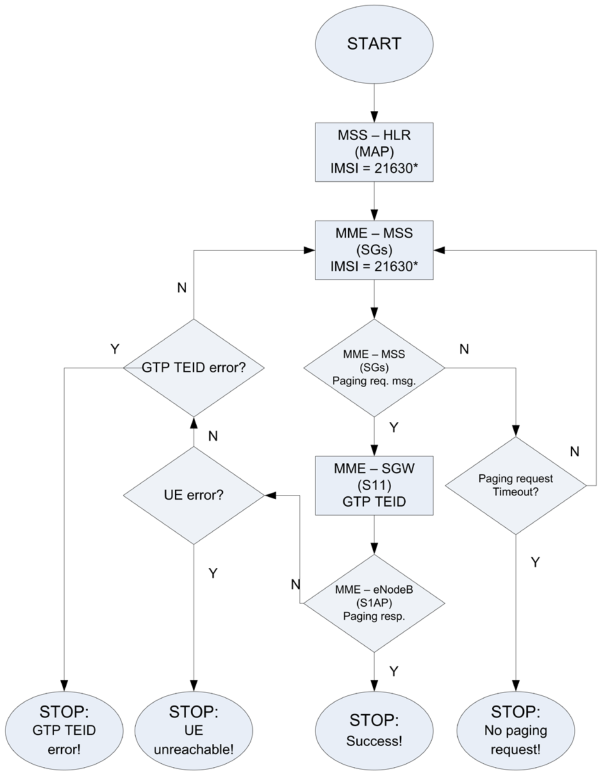

Fig. 4. Workflow of the call analysis.

No Paging

Some S1AP CDRs were opened with "No paging", which means they opened without an initial paging. Based on the standard this should not happen, because at the first step of S1AP establishment the MME sends paging to the eNodeB, based on the M-TMSI. The irregular CDR assembling procedure looked like the following: during a not-closed transaction, the eNodeB sent an InitialUEMessage to the MME. (The InitialUeMessage is normally the second message after the paging, and its purpose is to establish the data connection between the UE and the core network). In the examined cases there were no initial paging messages, because there was an active, not-closed connection. This resulted in a seemingly irregular CDR assembly scenario. There are two conclusions of this example: (1) it validates the right behavior of the CDR creation, because such cases are not standard, and (2) it occurs only in few cases, meaning that this can be caused by user equipment error.

V. USE CASES

Compared to the examined calls we should investigate the control traffic on the most important links. During these calls we know only one identifier in the beginning - such as the MSISDN. The first step is to find messages that carry that identifier (in the given time-range), and then to look for further, important, maybe temporary identifiers within those messages. In the further steps we can then initiate searches for those temporary identifiers, to find the corresponding S1AP signaling information.

A. Everything is normal

As a first case we present a successful call scenario. Since we know the MSISDN, the IMSI can be found in the MSS-HLR link, as can be seen in the output depicted by Fig. 5. In the next step, the GTP identifiers were collected - based on IMSI - in the MME-SGW interface. Thanks to the GTP identifiers, the required signaling packets can be matched on the S1 interface. As the output shows, the paging was successfully sent.

B. Erroneous case

In this example our test voice-call was unsuccessful: it got forwarded to voice-mail, however we know the user was reachable during that time. Regarding the operator's work, the search was similar to the previously illustrated case. At first, we found the IMSI on the MSS-HLR link (by using the MSISDN and the time as the search criteria), then based on the GTP identifier, we found an interesting message (see typesetted, timestamped).

Paging was sent, but still we received an "Ue unreachable" message. There can be many reasons for this, including UE failure, loss of coverage, etc.. Although this method helps us to investigate a lot of similar issues, the greatest problem still remains the parallel search on a lot of links. This requires a lot of time, and not just tens of minutes but even some hours could be needed for a proper examination.

C. Automating the fault management process

The analysis of one complete call includes data gathering and investigation from all the links that can be associated with the different aspects of call establishment. This requires a lot of time and deep knowledge of the system interfaces. Investigation of one failure requires hours of work; however with S1AP monitoring, we will have the opportunity to get all data from the links at once - by only knowing one identifier. Automating this requires of course some development, but it makes the work of the operator's engineers more comfortable and effective. Fig. 4 presents an automated analysis method, where one request can fire off sequential, automated operations. This starts with only one known parameter (IMSI), and provides a trace result that includes all related messages. Analysis time can be decreased with at least one order of magnitude – when compared to the above described, mostly by using a manual method that involves the intensive usage of the CDR Viewer.

VI. CONCLUSION

This paper is focusing on monitoring and analysis of the Evolved Packet Core (EPC), in order to provide traffic analysis methods for the Voice over LTE service. After briefly summarizing the elements of the LTE EPC, we briefly discussed the requirements and a solution for network-wide traffic monitoring in the core. Furthermore, there are some

```
13:28:41.870 >694> sendRoutingInfo imsi=21630[XXomittedXX]969 RoamN=3630[XXomittedXX]262
13:28:29.201’553’3 <J92< creat session resp 95CF8055 9F5160E3
13:28:29.196’627’5 >J92> creatsession 95CF8055&AB21E013 21630[XXomittedXX]969
13:28:30.043 <JB1< InitialUEMessage  m-tmsi=CA3AE055 enb-ue-s1ap-id=000E34
13:28:29.360 >JB1> Paging m-tmsi=CA3AE055
13:28:30.055 >JB1> InitialContextSetupRequest 9F5160E3
13:29:09.497 <L18< imsi=21630[XXomittedXX]969 UE unreachable
```

Fig. 5. Signalling on the MAP interface

issues brought up due to the ciphering of most of the S1AP messages; these need to be deciphered, for which the proper keys are required to be collected and utilized. Handling this is a difficult engineering problem, because we have to know the contexts between the protocols, keys and identifiers. We have presented a method for S1AP session data record assembling, the key parameters and the general method for their assembly. As a main part of the paper, we have showed methods on how to extract valuable information from these CDRs for various use cases, including basic events, attach cases or tracking area related cases. Furthermore we showed analysis methods for S1AP CDRs for incomplete, or other erroneous cases, and analysis use cases when the operator only knows a single identifier (such as the MSISDN), and a time range to search in. We presented the methods how to gather cross-correlated data on specific fault management use-cases, especially for unsuccessful voice calls. It is clear, that some of these analysis steps can and should be made automatic: we suggest further development in that direction, too. Developing the network monitoring system in parallel with the rising expectations of the customers is very important here.

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Autonomous Vehicles and Smart Mobility Related Technologies

Cristina Olaverri-Monreal *Member, IEEE*

***Abstract*—Smart Mobility is associated with a sustainable mobility performance that in turn affects quality of life. Current technology makes it possible to compile massive amounts of real-time data to optimize the urban infrastructure, consequently improving the efficiency of public transport services, from both user and service-provider perspectives. The analysis of these location-based data enables us to determine which services could be useful for citizens at a certain time, for example, thereby improving citizens' ability to navigate the most efficient routes and modes of travel. Various aspects of technologies that enable smart mobility in cities, including autonomous vehicles are presented in this paper.**

***Index Terms*—Smart Mobility, Internet of the Things, Ubiquitous Sensor Technology, Smart Cities, Autonomous Vehicles.**

I. INTRODUCTION

Transportation, parking and traffic management are decisive aspects in the characterization of Smart Cities. Other factors include for example: information and communication systems; energy efficiency and sustainability initiatives; citizen engagement and empowerment; open data and government transparency; public safety and security [1]. Mobility serves as one of the additional classification categories for Smart Cities that have been defined within the EU project "European Smart Cities" [2] together with: economy, people, governance, environment, and living Smart Cities. To determine if societal needs or technological trends affect this mentioned selection of parameters, it is crucial to investigate the role of the citizens, as future users to find out their needs and guarantee a citizen-friendly living environment. Taking this into account helps prevent unnecessary growth and development of undesirable or useless information and infrastructure, which would only overwhelm and upset citizens and negatively affect their quality of life.

The knowledge resulting from the analysis of massive amounts of data compiled using technology can assist in the creation of extensive social benefits [3]. Particularly, digital technologies derived from real-time data optimize the urban infrastructure, therefore improving efficiency and effectiveness of citizen navigation. The growing trend towards ubiquitous information communication that results from pervasive computing is particularly embodied in today's smart devices, which already integrate a variety of cost-efficient embedded sensors and facilitate the acquisition of data to study mobility patterns [4]. Research related to these location-based data enables us to take a decision about which services could be useful for citizens in order to improve the efficiency of public and transport services.

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This paper presents various aspects of technologies that enable a smart, sustainable mobility in cities and is organized as follows. The upcoming section reviews the state-of-the-art and related work in the area of Urban Mobility and Smart Cities. Section III demonstrates the importance of the Intelligent Transportation Systems (ITS) field. Section IV introduces Autonomous Vehicles and portrays their role in Smart Mobility. Concluding thoughts are stated in the final section of the paper.

II. STATE OF THE ART AND RELATED WORK

A. *Smart Cities*

Smart Cities are associated with a high quality of life. Quality of life is determined through several diverse factors that include sustainable transport systems, safety and security, the availability of green open spaces and other basic services. Other less obvious indicators are actively promoted and elevated citizen interaction and social inclusion, which can be embodied by shared public spaces for cultural and sport activities, for example [7].

The European Initiative on Smart Cities aims to support cities and regions in taking ambitious measures to progress by 2020 towards a 40% reduction of greenhouse gas emissions through sustainable use and production of energy [8]. Similarly, the European Innovation Partnership on Smart Cities and Communities (EIP-SCC) intends to develop collaborative and participatory approaches for cities, industry and citizens to improve urban life through sustainable solutions. This includes more efficient use of energy, transport, and Information and Communication Technologies (ICT), thereby reducing overall energy demand and increasing the use of renewable energy sources [9]. There are already over 14 European projects that have their focus in the sectors "Energy", "Transport & Mobility" or "ICT" that resulted from this European Partnership [10]. Energy-related aspects are addressed by 9 of the 14, while 3 cover all the areas Energy, Transport & Mobility and ICTs. In the context of transportation, the European FP7 program already funded projects that addressed sustainable management of urban waste [11] or intelligent urban bus systems [12].

B. Smart Urban Mobility

In the report for the *Sustainable Mobility Project 2.0 (SMP2.0)* within the World Business Council for Sustainable Development [5] the authors described 22 indicators for parameters and methodologies to be used by cities to identify their sustainable mobility performance. Smart urban mobility intersects with several of these important indicators such as congestion and delays, commuting travel time, mobility space usage, access to mobility services, traffic safety, comfort and pleasure, intermodal connectivity and occupancy rate. It additionally connects a range of technologies such as vehicle manufacturing, transport information systems, communications technologies and logistics.
These mentioned parameters and their relationship with Smart Mobility will be further addressed in this paper that expands the individual areas described in [6].

According to [13] European cities have better public transit and a stronger focus on sustainability and low-carbon solutions than other cities in the world. The cities in Europe that in 2014 had developed the most innovative actions related to infrastructures and technologies are Copenhagen, Amsterdam, Vienna, Barcelona, Paris, Stockholm, London, Hamburg, Berlin, and Helsinki. However, there is still room for improvement at a European level aiming at a decrease of pollution and carbon dioxide emissions. For example, several European cities have already started plans to restrict traffic and parking in downtown areas, with interruption of the production of industrial plants, or via speed limitations [14] to alleviate the current high levels of carbon dioxide output.
As an example, the city of Amsterdam is providing its citizens with technologies that ensure a better quality of city life within the framework of the Amsterdam Smart City Project, such as free Wi-Fi and a new optical fiber network. Moreover, “smart grid” technologies for transportation are contributing to a reduction of emissions by guiding trucks to available unloading zones, controlling traffic lights and bridges and providing residents with personalized travel advice [15], [16].

C. Connectivity

To receive the Smart label, cities must rely on broadband connectivity [3]. A concept representing the elements that constitute a Smart City using digital technologies is proposed in [17]. According to the authors, a Smart City differentiates itself from other cities by exhibiting an assemblage of various components for understanding and coordinating urban problems with innovative technologies in an effective and feasible manner. The framework concept covers different dimensions including urban governance and functioning, infrastructure organization, transport, and energy.

There has been a drastic increase in the number of systems which rely upon sensor data collection. This in turn generates a large body of information and sources to analyze. Furthermore, there is an overall spread in the application of digital technologies through the deployment of physical sensors in homes, buildings and cities. This pervasive computing context presents the possibility of designing Smart City applications which base their functioning on intelligent technologies that simultaneously reside in other applications that communicate with each other. This integration of ICT in conventional city infrastructures is part of the strategic initiatives of the international joint projects of the Connected Smart Cities Network described in [18].

The design and application of information and communication technology to create environmental benefits, the so called Green ICT, plays a decisive role in reducing carbon emissions. As stated in [19], communication networks and the related infrastructures that consider energy efficiency could create a 20% reduction of global CO2 emmisions by 2030. Enhanced connectivity through ICT could significantly affect Smart Mobility by reducing congestion, emissions, and resource consumption through an overall decrease in the need to travel [19].

In this context, mobile operators can play a role in four key aspects of smart city services [20]:

- Connectivity: connecting city infrastructure and personal mobile devices to central servers;
- Data aggregation/analysis: combining data from multiple sources to gain new knowledge;
- Service delivery: delivering real-time information to citizens and devices regarding events in the city;
- Customer interface - providing customer support

In recent years a huge amount of work has been dedicated to sensors supported by Internet of Things (IoT). Intelligent displays in appliances as platforms to share information with additional mobile devices, to manage a healthier diet or to save energy in the household are some of the applications based on IoT. But at a citizen level, big expectations have been put into the IoT as technology for an ubiquitous information access via the Internet. The large concentration of resources and facilities that attract people from rural areas to cities [21] is causing a population growth that is making it increasingly challenging for city governance and politics to enact efficient city management. Moreover, the current 54% of world’s population that lives in urban areas is expected to increase to 66% by 2050 [22].

There is great potential in the IoT in developing and connecting technologies which assist in improved city management and better quality of life for the growing citizenry. Through the Internet of Things, products can be connected to create more efficient transportation systems. The European Commission predicts that by 2020 devices connected to the internet will number between 50 and 100 billion [23] and will form the base for cooperation frameworks for access to knowledge resources.

A vision of the Internet components, Internet of Things and Internet of Services (IoS) transforming a Smart City into an open innovation platform has been specified in [24], [25]. The authors also present a generic concept implementation

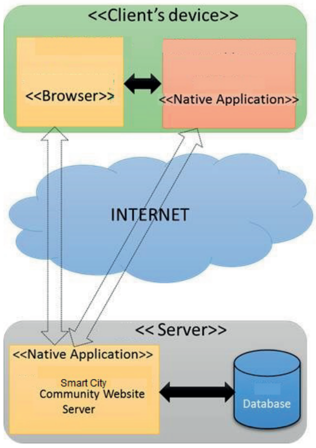

Fig. 1. Client-server architecture to share urban information (adapted from [27])

based on Ubiquitous Sensor Networks.

As the use of IoT to support sustainable development of future Smart Cities entails several difficulties that are related to the various natures of the connected objects, a work was proposed in [26] that described a management framework for IoT. Within this system, objects are represented in a virtual environment. Through the use of cognitive and proximity approaches the authors make it possible to select the most relevant objects to Smart Cities.

D. Collaborative Approaches

Collaborative teamwork based on shared mental models is required to create frameworks for understanding joint work [28], [29]. This work has to be collectively conceived and shared by several users relying on activity awareness. Just such a collaborative approach is crucial in the advancement of Smart Cities, at both local and intercity levels.

Citizen feedback on issues and suggestions for improvement of services [30] are a fundamental requisite for a sustainable, efficient city. Modern pervasive communication technologies make it possible to share widely available information between citizens and public authorities so that a subsequent data analysis can be performed by taking advantage of crowd-sourcing data technologies. Figure 1 shows an example of information client-server architecture to share urban information.

As local and personalized solutions are expensive to develop and maintain, and can affect the mobility route choices left to other road users it is essential to develop frameworks and platforms to share knowledge and best practices. To this end, methodologies that capture data related to citizens preferences and habits help to identify and understand their needs and goals. For example, through measurements to establish relationships between variables such as travel origin and destination and others such as recommended route. In the Smart Mobility cooperative context, the authors in [31] investigated the effect of the number of vehicles and available road capacity on the level of congestion, with a focus on modifying route choices. They studied the relationship between travel demand and driving travel times, and assessed the benefits of different scenarios. In the work, they conclude that social consideration related to routing behavior affects congested cities positively.

III. Intelligent Transportation Systems

Roads are a shared space for people and vehicles. In the same manner that applied sensor technology is fundamental in IoT and IoS, sensors can be integrated into road infrastructure to recognize and monitor a wide repertoire of activities related to the transportation sector. According to [32] the European Commission's "ITS action plan", or action plan for the deployment of intelligent transport systems aims to make road transport and its interfaces with other transport modes more environmentally friendly, efficient and safer. To this end, European standards, for example for the exchange of data, need to be set. Moreover, the EU encourages the use of different transport modes to reduce congestion and greenhouse gas emissions, decrease the number of road traffic accidents and energy consumption.

According to [33] production- and consumption-based emissions that result from cities account for more than 80% of the world's greenhouse gas (GHG) emissions. Some cities, are so badly affected by pollution that their citizens are advised to stay indoors or restrict vehicle use. As a consequence, finding energy supply that directly involve mobility systems has become a priority. A change in the mode of transport, travel route and the integration of real-time information can lead to better average car speed and an improved traffic flow, as it has been shown in Singapore with 27 km/hour, compared to 16 km/hour in London and 11 km/hour in Tokyo [34], [16].

In the context of a more efficient use of energy in the transport sector, the steady integration of electric cars will contribute to a decrease of fuel consumption. Automobile manufacturers, facilitated by reductions in battery prices, offer increasingly affordable vehicles without internal combustion engines. According to the predictions of *Bloomberg New Energy Finance*, 35% of the cars that are sold in 2040 will be electric. It is expected that by 2020 they will represent a more economic option than gasoline or diesel cars in most countries [35]. Despite their rapid growth, plug-in electric cars represented only 0.1% of the one billion cars on the world's roads by the end of 2015 [36]. It is clear that major efforts still need to be made to promote electric driving, which, though considered beneficial for the environment, is not yet widely accepted by the public [37].

A. Mobility Patterns

The monitoring of mobility patterns can be used to study driving behavior for improving traffic flow through a reduction of traffic congestion and an increase in road safety [38], [39]. Mobility patterns are the big-picture sets of information that show people's habits and routes. Therefore, mobility pattern information is crucial in providing personal multimodal mobility services as it can guide technological applications in suggesting travel routes and creating new habits.

Crowd-sourcing data available through mobile devices and processed through cloud-based architectures facilitate the monitoring process to support travel pattern changes based, for example, in new routing recommendations. Figure 2 depicts a scheme to acquiring, storing, processing and analyzing mobility-related data using smartphone sensors. Such an approach permits the users to benefit from additional services, such as recommendation of alternative route paths and feedback related to current driving patterns for a shorter traveling time or fuel savings. Moreover, modification of mobility habits can be encouraged through gamification approaches, awarding commuting users with discounts for certain services if they avoid rush hours or use public transportation. Serious games can additionally modify driver behavior contributing educated drivers in avoiding unsafe actions by using a scoring system [45]. Smartphone technology can also be for example applied to give a good approximation of the vehicle occupancy rate as a parameter for smart mobility.

Urban mobile data makes it possible to develop intelligent mobility concepts in which replacing private vehicle use with public transportation use and a reduction of traffic create an efficient flow of the remaining vehicles, consequently lowering total carbon emissions. The goal is to achieve a balanced optimization of transit use and personal vehicles, for a faster commute and environmental benefits. To this end, improvements in urban mobility have been initiated through planning of routes in real-time. As several factors such as weather, maintenance work, accidents, public events, etc. determine the use of public transportation but also of private vehicles [3], it is important to provide clear and accurate real-time information that allows commuters to make decisions regarding the use of public transportation or personal vehicles, and also to select the mode of transportation that better fits the needs of everyone (Figure 3).

The use of mobile devices in a road context by drivers and VRU is rapidly increasing. In a vehicular context, proper in-vehicle warnings and function location that enhance visibility and reduce the distraction potential has been the design focus by automotive manufacturers for many years [40]. However, this has not been extended to mobile devices that are increasingly being used in a road context, and most mobile solutions tend to neglect the risks related to the influence of mobile phone usage in a situation where traffic needs to be considered [41]. In addition, the basic needs of pedestrians regarding for example routing approaches are not been considered in most of the cases [42]. Therefore, the use of mobile devices is becoming a very prominent safety issue,

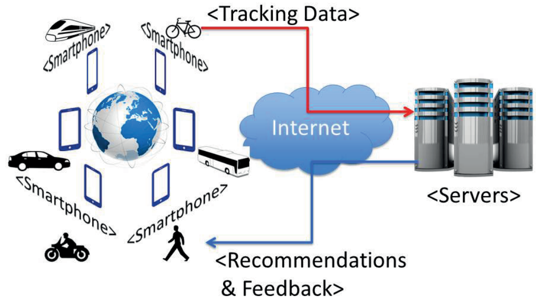

Fig. 2. Scheme for the acquisition, storage, processing and analysis of mobility-related data using smartphone sensors [4]

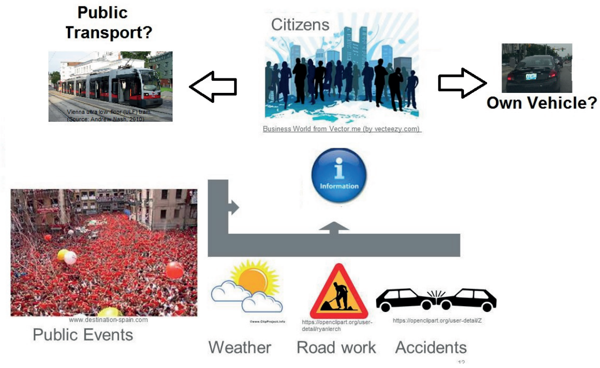

Fig. 3. Selected factors that determine the use of public transportation or private vehicles

particularly relevant in urban environments with high traffic density. Pedestrians and other vulnerable road users (VRU) can be supported by mobile applications for use in public spaces or transport in their route choices to minimize potential dangers such as distraction. Vehicle-to-pedestrian (V2P) and pedestrian-to-vehicle (P2V) communication technologies for exchanging information work towards improving road use and safety through warnings for users regarding potential dangers. Research, mostly based on GPS data, has been developed in this field. For example, the authors in [43], [59] developed a system based on wireless pedestrian-to-vehicle communication which was able to issue warnings of collision risk.

Since perception and communication are essential for VRU safety, theoretical models and studies have been performed in real-world environments to test the reliability of several systems. A cooperative system as a combination of both approaches and that integrates the outputs of the communication and perception systems was proposed as the optimal solution by the authors in [44].

Fig. 4. Cooperative driving in which visual data related to the safety distance is provided to the vehicle behind in real-time [49]

B. *Traffic Data and Cooperative Systems*

Urban traffic data can be acquired through sensors available on road infrastructure, mobile devices or the cars themselves. For example, the authors in [46] deployed Bluetooth scanners along the freeway/arterial network in the road proximity to study and characterize urban traffic conditions. The collected travel time information enabled an effective traffic management, control and flow optimization as well as the basis for improving existing routing algorithms, positively affecting costs related to logistics and reducing the environmental impact.

Exchange of information through cooperative systems that broadcast traffic data is imperative to enhance road safety. To this end, urban environments provide the test bed conditions required to perform realistic experiments with massive amounts of valuable data. This allows for the evaluation of a variety of protocols, as well as interaction with in-vehicle systems and services. For example, within the design and development of the See-Through System [47], [48] experiments under real conditions were performed in order to test potential connectivity issues and data transmission delays using the 802.11p standard wireless communication protocol.

In a joint effort to implement safety and decision-making processes at an individual level, further cooperative approaches can increase the drivers visual awareness, for example of safe distances. Through the stereoscopic capturing and processing of images by rear cameras information can be garnered to determine if the safety distance is appropriate [49]. Figure 4 illustrates the idea.

IV. AUTONOMOUS VEHICLES

Realistic Vehicular Ad Hoc Networks (VANETs) and the related technologies, for example those implemented in autonomous car applications, will change cities as we know them. As stated by the executive director of the car manufacturer Ford, Mark Fields, “2016 will be a revolutionary year for automotive and transport, in which we will see radical advances that will change the way to move”. According to the International Organization for Road Accident Prevention [53], human error is the cause of 90 percent of the road accidents. To alleviate the number of accidents, the introduction of autonomous vehicles on our roads represents an opportunity for increased road safety as the automation will make driver intervention in the control of the vehicle unnecessary (Figure 5).

Other advantages of the use of driverless vehicles will be an uninterrupted traffic flow, energy consumption reduction and road capacity increase through a decrement of the aerodynamic impact on the vehicles, leading to a minimization of the distances between them. This will be ensured by sensors that will control the spaces between vehicles and the observance of the safety distance. Autonomous trucks with automated features have already successfully platooned across Europe to increase environmental, safety and comfort benefits [54].

Autonomous Vehicles (AV) can work as network nodes in a VANET, being thus capable of identifying exceptional situations in which it is difficult to plan appropriate measures (i.e. road works, unforeseeable traffic situations like accidents that result in a traffic congestion or missing map data). Under these circumstances, vehicle control localization and mapping could be conducted based on data available from other vehicles in the same VANET [50]. Alternatively, the control could be relayed back to humans, through an emergency Take Over Request (TOR). Here prediction systems would play a crucial role [51]. Assessment of the driver’s state and the driving environment is essential in promoting road safety in both manual and automatic driving paradigms where the monitoring tasks are either performed by the driver or by the system. In this line of research a cost effective mobile application to measure gaze behavior and analyze road conditions was presented in [52]. The application worked on a mobile smart device in an automatic driving paradigm where a TOR was triggered in case of an unexpected road situation or in a manual driving paradigm to avoid inattentive driving.

It is expected that AV represent more opportunities to develop innovative in-vehicle technology for entertainment or information purposes that will require a cockpit design adaptation and modification of the car controls for more flexibility of movement within the vehicle. In this context, some automotive manufacturers are already performing research on new designs concerning the steering wheel. For example the authors in [55] investigated the effect on the driver of taking over a control request from a highly automated vehicle using a geometrically transformed steering wheel. Results concerning the reaction time when taking over control of the vehicle were discussed.

A complete vehicle interior redesign without a steering wheel or pedals seems unlikely though, as it would impede adequate response to a TOR in an unexpected situation or switching to manual control, which would firstly affect safety and, in addition, User Experience (UX) or joy of use.

The potential boredom and road monotony associated with higher automatism of vehicles might lead to a reduction in driver situational awareness (Table I depicts the levels of automation). This condition will have to be compensated by new ways of prominent and understandable continuous feedback that might, on the other hand, decrease the joy of use. Research in the field is imperative to guarantee an optimum level of automation that is balanced by an appropriately demanding cognitive workload.

It has been shown that perceived usefulness, trustworthiness and ease-of-use have a direct impact on consumers' behavioral in their intention to use a specific tool [56]. It is not yet clear if any reduction in the joy of driving due to automation will be found to be acceptable by those who enjoy driving. Trust also plays a decisive role in the adoption of the new self-driving car technology, as the drivers needs to accept occasional autonomy of vehicle and cede part of their own control. In the same context if the passenger in an automated vehicle is not able to verify the authenticity of the provided information (e.g. in case of information broadcast by inter vehicular wireless technology), it might jeopardize perceived trustworthiness of the technology.

In this line of research, the interaction of autonomous vehicles with other road users has been investigated in several works but until now it has been only based on simulated scenarios or survey studies [57], [58]. However, the authors in [59] performed a field test with driverless vehicles provided with full autonomy notifying pedestrians through a smart phone application that an autonomous vehicle was approaching. The goal of the work was to test if such a message would help pedestrians to develop a trust in the autonomous vehicle technology. The participants in the experiment stated that the application supported them in the verification process of trusting autonomous vehicles as a reliable safe technology, as they realized that it was as safe as a conventional vehicle.

The profile of future AV customers or who will maintain ownership of the vehicles is not yet clear, for example whether they will be private property of the suburban commuter population themselves. Other unknown social and cultural consequences of increased AV usage are topics for future research, for example: could the comfort that AV provides cause an increase in population relocation to suburbs, and lead to environmental problems? If self-driving cars become popular among citizens, and if downsides such as potential hacking exposure or safety concerns are surpassed, their traveling comfort and privacy will seriously compete with the use of public transportation.

It is expected that Autonomous Vehicles will foster the sharing of vehicles without the need of owning them. On the other hand, car ownership is extremely popular among younger people, as shown in the 2015 Continental Mobility Study [37]: of those surveyed 83% of Germans used their own car, while 17% used a family car and only 1% used rental cars or relied on car sharing. In the US the results regarding shared use of vehicles showed that 94% of the participants in the survey used their own car, 5% used a family car and 1% used a rental or car sharing vehicle. Autonomous Vehicles represent an opportunity to redefine individual mobility, as they create more opportunities for car sharing (including ridesharing or car pooling) and, as has already been observed,

TABLE I
LEVELS OF DRIVING AUTOMATION FOR ON-ROAD VEHICLES. ADAPTED FROM [60]

Autonomy Degree	Description	Examples
1. Driver only	Vehicle entirely under human control but might have some automated systems.	Cruise control, electronic stability control, anti-lock brakes.
2. Driver assistance	Steering and/or acceleration are automatic but the driver must control the other functions.	Adaptive cruise control: distance to leading car maintained; Parking assistant: steering is automated. Driver controls accelerator and brakes.
3. Partial autonomy	Driver does not control steering or acceleration but is expected to be attentive at all times and take back control instantaneously when required.	Adaptive cruise control with lane keeping. Traffic jam assistance.
4. High autonomy	Vehicles are able to operate autonomously for some portions of the journey. Transfer of control back to the human driver happens with some warning.	Prototype vehicles.
5. Full autonomy	Vehicle is capable of driving unaided for the entire journey with no human intervention; potentially without a human in the car.	None.

Fig. 5. Autonomous vehicle passenger that does not require overseeing the driving task.

can reshape our current societal business organization by enabling new business opportunities.

A lower number of cars per household would be necessary if autonomous vehicles are used, as they could be called through mobile applications and move to the location where they are needed. They will also demand fewer parking lots and require reduced road space, as they allow for narrower city lanes and therefore more room for pedestrians and green spaces. This in turn will count towards an improvement in quality of life in cities.

Whether road redesign will be required (i.e. by adding dedicated lanes for AV) or adaptation of infrastructure such as marking for road signals, or even VRU marking for better recognition, is necessary, is not yet clear; but in this case it will represent an opportunity for improvement.

V. CONCLUSION

This paper gives an overview of different aspects and factors that determine the qualification of "Smart Mobility". Even if a large number of projects and initiatives have been started to provide citizens with efficient and effective services, there is still room for improvement, particularly concerning environmental benefits. Applied sensor technology is fundamental in sharing knowledge and fostering communication, as well as in gathering feedback from citizens, in particular to facilitate the acquisition of data to study mobility patterns. Environmentally friendly, efficient and safer road transport that fosters multimodal transport through the exchange of data, is a crucial objective to reduce congestion and greenhouse gas emissions. To this end, sensors can be applied into road infrastructure to recognize and monitor a wide repertoire of activities related to the transportation sector. Autonomous driving will definitely affect current mobility and the driving experience. It will have implications for regulatory, social and economic sectors, as well as in urban planning and the various factors affecting smart mobility.

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Survey on Monocular Odometry for Conventional Smartphones

Gergely Hollósi, Csaba Lukovszki, István Moldován, Sándor Plósz and Frigyes Harasztos

***Abstract*—In the last decade huge amount of research work has been put to realize indoor visual localization with personal smartphones. Considering the available sensors and their capabilities monocular odometry may provide a solution, even regarding strict requirements of augmented reality applications. This paper is aimed to give an overview on the state of the art results regarding monocular visual indoor localization. For this purpose it presents the necessary basics of computer vision and reviews the most promising solutions for different topics.**

***Index Terms*—Computer vision, Visual Monocular Odometry, SLAM, Survey**

I. INTRODUCTION

Due to the increasing capabilities and penetration, more and more applications are available on smart-phones to ease our everyday life. In the last decade huge research work has been put on indoor location-based applications, among these the augmented reality based applications demand the highest requirements, mostly expressed in real-time capability and accuracy. Based on the sensors available in recent smartphones and their computational and storage capabilities, a real-time implementation of monocular visual relative pose estimation seems to be the key to achieve the overall goal.

Besides, this topic presents a great research interest, and high effort has been put on providing scalable and accurate solutions to satisfy the real-time requirements. Traditionally, the problem of visual pose estimation is discussed as the Structure from Motion (SFM) [1] [2] problem, where the main goal was the off-line reconstruction of a 3D structure from pictures taken from different viewpoints. During the reconstruction process the viewpoints of the camera are also calculated, but the problem formulation does not focus on the relative pose estimation of sequential images. Moreover the family of SLAM (Simultaneous Localization and Mapping) algorithms focuses on the environment modeling (map building) and the relative camera pose estimation simultaneously [3]. To overcome the real time and accuracy requirements these solutions induced the PTAM (Parallel Tracking and Mapping) [4]. In the meantime, the problem has been also targeted by another application field, the odometry. The original requirement of the monocular Visual Odometry (VO) [5] [6] was to accurately determine the relative pose of a rover.

In this paper authors are engaged to give a theoretical overview of the monocular odometry problem and its solutions. Also, some of the implementations are emphasized that seem to able to cope with the strict requirements even in mobile environments.

During the discussion the authors focus on the capabilities of the recent smartphones. Common smartphones are equipped with a thin-lens perspective camera, that can be modeled with an ideal pin-hole model [7], and they are also equipped with IMU (Inertial Measurement Unit) integrating gyroscope and accelerometer, while having reasonable capacity for storage and processing. Regarding the motion of the device the following discussion considers 6dof (degree-of-freedom).

II. THEORETICAL BACKGROUND

Monocular visual odometry tries to determine the pose and location of a device mainly using visual perception aided by a couple of auxiliary sensors (e.g. gyroscope or acceleration sensor). The common implementation of visual perception is a monocular camera which provides continuous stream of frames at a variable or uniform time instants.

A. Projection model

The camera has a couple of internal parameters which are typically fixed and known a priori (e.g. by calibration). The most important characteristic of the camera is the projection model which projects three dimensional world points onto the image:

$$\mathbf{u} = \pi(\mathbf{p}_\mathcal{C}) \tag{1}$$

where $\mathbf{p}_\mathcal{C} = \left[x_\mathcal{C}, y_\mathcal{C}, z_\mathcal{C}\right]$ is a three dimensional world point in the reference frame of the camera, $\mathbf{u} = \left[x, y\right]$ is the projected point and $\pi(\cdot)$ is the projection model. It is essential to mention that in case of monocular systems the $\pi(\cdot)$ projection model is invertible only when the depth $d_\mathbf{u}$ of the model point is known:

$$\mathbf{p}_\mathcal{C} = \pi^{-1}(\mathbf{u}, d_\mathbf{u}) \tag{2}$$

We can see that monocular systems have the huge drawback of loosing the depth information while recording frames.

In practice the projection model is considered to be linear in homogeneous space, i.e. it can be represented by a matrix product (commonly referred to as the pinhole camera model). Let $\mathbf{X}_\mathcal{C} = \left[X, Y, Z, 1\right]^T$ be the homogeneous coordinates of a three dimensional point in the reference frame of the camera.

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In this case the projection model can be expressed with a K intrinsic camera matrix:

$$\mathbf{x} = \mathbf{K}(f)\left[\mathbf{I}_{3\times3}|\mathbf{0}_{3\times1}\right]\mathbf{X}_{\mathcal{C}} = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \mathbf{X}_{\mathcal{C}} \tag{3}$$

where f is the focal length of the camera and $\mathbf{x} = \left[\lambda x, \lambda y, \lambda\right]^T$ are the homogeneous coordinates of the two dimensional projection. It is easy to see that the projection model is not invertible.

To represent the camera movement in the world frame we assign a $\mathbf{T}_k$ rigid-body transformation to each frame I_k at k time instants which contains the orientation ($\mathbf{R}_k$) and the location ($\mathbf{C}_k$) of the camera. The transformation can be expressed as a 4×4 matrix as

$$\mathbf{T}_k = \begin{bmatrix} \mathbf{R}_k & \mathbf{C}_k \\ 0 & 1 \end{bmatrix} \tag{4}$$

A fixed world point $\mathbf{X} = \left[X, Y, Z, 1\right]$ can be projected at the k-th image frame as

$$\begin{aligned} \mathbf{x}_k &= \mathbf{K}(f)\left[\mathbf{I}|\mathbf{0}\right]\mathbf{T}_k^{-1}\mathbf{X} = \\ &= \mathbf{K}(f)\left[\mathbf{R}_k^{-1}| - \mathbf{R}_k^{-1}\mathbf{C}_k\right]\mathbf{X} = \\ &= \mathbf{K}(f)\mathbf{P}_k^e\mathbf{X} \end{aligned} \tag{5}$$

where $\mathbf{P}_k^e$ is commonly called as the extrinsic matrix describing the world-to-camera transformation. Eq 5 is the most basic and substantial constraint in the monocular visual odometry systems.

The goal of the monocular visual odometry algorithms is to determine the $\mathbf{P}_k^e$ extrinsic camera matrices or the $\mathbf{T}_k$ rigid-body transformation of the cameras mainly based on (but not exclusively) the visual information encoded in frames.

B. Projection distortion

An accurate algorithm must take into consideration that the projection model of the classical pinhole camera is only an approximation. Real cameras always have some non-linear distortion which is basically modelled as *radial* distortion, however, other distortion models also exist (i.e. tangential distortion) [8]. Radial distortion depends on the radial distance from the radial distortion center (typically the principal point) and it is represented as an arbitrary function:

$$\hat{x} = x_c + L(r)(x - x_c) \qquad \hat{y} = y_c + L(r)(y - y_c) \tag{6}$$

where $r^2 = (x - x_c)^2 + (y - y_c)^2$ is the radial distance and x_c, y_c are the radial centers (commonly considered as zero). In practice, $L(r)$ is represented as a Taylor-series

$$L(r) = 1 + \kappa_1 r + \kappa_2 r^2 + \kappa_3 r^3 + \cdots \tag{7}$$

where κ_i are the radial distortion coefficients. In practice only the lower coefficients ($\kappa_1, \kappa_2, \kappa_3$) are used.

C. Visual information retrieval

Visual odometry solutions are based on visual information encoded in the sequence of image frames. We can distinguish two widespread methods: intensity based *direct* methods and *feature* based methods.

1) Direct methods: In general, direct methods uses the $I_k(\mathbf{u})$ intensity map of the image, which represents the brightness of the image pixel coordinate or – rarely – the RGB vector. The intensity map can be either quantized (i.e. pixel accuracy) or continuous (i.e. subpixel accuracy), however, the latter requires some kind of filtering or interpolating algorithm, that in some cases can cause information loss.

2) Feature detection: Feature based methods are working on point projections using *feature detection* and *feature extraction* algorithms that are able to detect and match the same points on different images without preliminary geometric knowledge. This way, visual odometry solutions are simplified to use only projections of real 3D landmarks. The efficiency of these algorithms can be measured by their invariance and speed. Invariance means that the detector can detect features which can be successfully matched even if the feature is rotated, scaled or suffered other transformations (e.g. affine transformation). There are a couple of such algorithms overviewed in [9], from that the most widely used are the Harris detector [10], the Scale-invariant feature transform (SIFT) which is based on Laplacian of Gaussian filters [11], the Maximally Stable Extremal Regions (MSER) [12], the Features from Accelerated Segment Test (FAST), Oriented FAST and Rotated BRIEF (ORB) [13]. Considering the overall requirements SIFT is the most promising, however due to its high complexity strict constraints restrict its application in mobile environments.

III. Feature based solutions

Feature based solutions have the attribute to detect features on the frames first then match them to the previous frame resulting in projection *tracks* over a couple of sequential frames. These tracks can then be used to compute the geometry of the scene and to recover the camera translations and orientations. This method utilizes only point geometry models and correspondences, this way the well established framework of multiple view geometry can be applied [7].

A. Theory

The most important term here is the pose estimation which is the process of estimating the extrinsic (and sometimes the intrinsic) matrix from point correspondences. Depending on the point pairs we distinguish between two types of pose estimation: in case of 3D-2D point pairs (i.e. the world points and their projections) it is called *absolute pose estimation* and in case of 2D-2D point pairs (i.e. the projection pairs on two images) we call it *relative pose estimation*.

1) PnP problem: The absolute pose estimation problem is generally called Perspective-n-Point (PnP) problem which has a couple of methods presented. The classical method for $n > 6$ point pairs is the DLT (Direct Linear Transform) method but it is known to be unstable and requires the camera to be calibrated [14]. For 5 or 4 points the [15] uses a polynomial technique which allows it to work well even in case of coplanar points. The EPnP solution is accurate for an arbitrary $n \geq 4$ point pairs and can handle planar and non-planar cases [16]. The P3P solution yields to finite number of solutions using only three point pairs as the smallest subset of points pairs [17]. The P3P solution has the advantage of using only three points in a RANSAC (Random Sample Consensus) framework to eliminate outlier point pairs thereby decreasing the required number of iterations.

2) Random Sample Consensus: Since feature matching is prone to result false matches a method is required to overcome this issue. It is common in image processing to use the minimal sample set to recover the parameters of a model and classify samples as inliers and outliers. The most noted algorithm is RANSAC which is widely used in the literature [18].

3) Relative pose estimation: The basic terms in relative pose estimation are the *fundamental matrix* and the *essential matrix*, both can be computed from projection pairs. The fundamental matrix is a 3×3 matrix ($\mathbf{F}$) satisfying $\mathbf{x}'^T \mathbf{F} \mathbf{x} = 0$, where projections ($\mathbf{x}$ and $\mathbf{x}'$) are of the same world point in two different images. The essential matrix ($\mathbf{E}$) uses the normalized image coordinates so it can be computed from the intrinsic camera matrix ($\mathbf{K}$) and the fundamental matrix as $\mathbf{E} = \mathbf{K}'^T \mathbf{F} \mathbf{K}$. The essential matrix is applicable to recover the pose of the cameras by decomposition [7]. A lot of methods are known to determine the relative pose of the cameras: the 8 point algorithm [19], the 7 point algorithm [7], 6 point algorithm [20] and 5 point algorithms [21] [22]. It is essential to mark that these algorithms differ in handling degenerate configurations (i.e. coplanar objects or cylinder containing the projection centers) and are unable to recover the scale of the set-up.

4) Bundle adjustment: The fundamental algorithms like the relative and absolute pose estimation and triangulation find the right solution only in case of noiseless measurements otherwise they minimize the algebraic error which has no physical meaning. It can be proven that the maximum likelihood (ML) solution of these problems is the minimization of *reprojection error*. If we have N cameras and M points in space, then we can assign a $\theta_n(K_n, T_n, \pi_n)$ projection model to each camera which contains the projection (π_n), distortions (K_n) and rigid body transformation (T_n) of the camera (i.e. intrinsic and extrinsic behavior). For a $\mathbf{p}_m$ point in space the projection for the camera n yields to $\mathbf{u}_{m,n} = \theta_n(\mathbf{p}_m)$. If the pixel measurements are $\overline{\mathbf{u}}_{n,m}$ then the optimization of reprojection error equals the expression

$$\arg\min_{\theta_n, \mathbf{p}_m} \sum_{n,m} |\overline{\mathbf{u}}_{n,m} - \theta_n(\mathbf{p}_m)|^2 \tag{8}$$

meaning minimization of the euclidean-distance between the measurements and the reprojected points.

As it is obvious from Eq. 8 that the reprojection error is not linear we need an iterative Newton-like solution to solve the minimization problem. The process of solving Eq. 8 with Levenberg-Marquardt iteration is specially called *bundle adjustment* [23]. Bundle adjustment is widely used in SLAM, SfM and odometry problems to refine a coarse solution or optimize the map and camera poses calculated before.

It is worth to mention that the special form of the projection equation yields to a sparse matrix which can be utilized to speed up the bundle adjustment and relax the memory and processing requirements. This method is called *sparse bundle adjustment* [24] [7].

B. Implementations

All of the solutions and implementations use the algorithms mentioned above but combine them in quite different ways.

1) PTAM: SLAM methods has the controversial problem of running at real-time speed while building an accurate map by a slow non-linear optimization process (i.e. bundle adjustment). Parallel tracking and mapping (PTAM) solves this problem by running two threads: one for the real-time tracking and one for the map building [4]. PTAM was designed to work in small-scale, e.g. to provide desk-scale augmented reality. PTAM has several extensions implemented, like new initializer based on homography or a relocaliser [25].

PTAM detects FAST features on a scale pyramid to provide scale invariance and uses these feature points to recover the geometry. The PTAM applies the 5-point algorithm to recover the initial camera relative pose (i.e. the fundamental matrix) and to construct the initial map. Hence, the process of PTAM odometry can be briefly described as follows:

- Tracking runs on its own thread and starts by detecting FAST features. A motion model is used to estimate the camera a-priori pose followed by projecting map points onto the image to detect feature matches and finally camera pose is refined from all the matches.
- The mapping thread selects keyframes at regular intervals based on a couple of conditions, then the thread triangulates new points and registers new projections. To refine the map, PTAM applies local and global bundle adjustments periodically.

The PTAM solution is capable to track the camera pose accurately and real-time thanks to the decoupled tracking and mapping processes, but its performance is limited by the number of landmarks registered in the map. This way PTAM is suitable only for small workspaces. One of the drawbacks of PTAM is the simple initialization process of the 5-point algorithm which is sensitive to planar degeneracy. It is worth to mention, that PTAM does not employ any methods to recover the accumulated odometry error (i.e. loop closing).

2) ORB-SLAM: ORB-SLAM realizes a rather complex visual odometry solution, however, it is based basically on feature detection and point geometry [26]. As its name suggests it uses ORB features to gather image information and provides odometry and 3d reconstruction simultaneously. Besides, ORB-SLAM provides re-localization and loop closing capabilities in order to make the process more accurate.

ORB-SLAM works pretty much like PTAM by running three threads parallel to provide real-time odometry. The *tracking* thread is responsible for real-time motion estimation by detecting ORB features and camera pose recovery. The *local mapping* thread calculates the 3d reconstruction of the map in the background for every keyframe chosen by the tracking thread. The *loop closing* thread is watching for map points to reoccur using bag of words model, and when it founds one, the loop closing corrects the loop by similarity transformation (see Fig. 1).

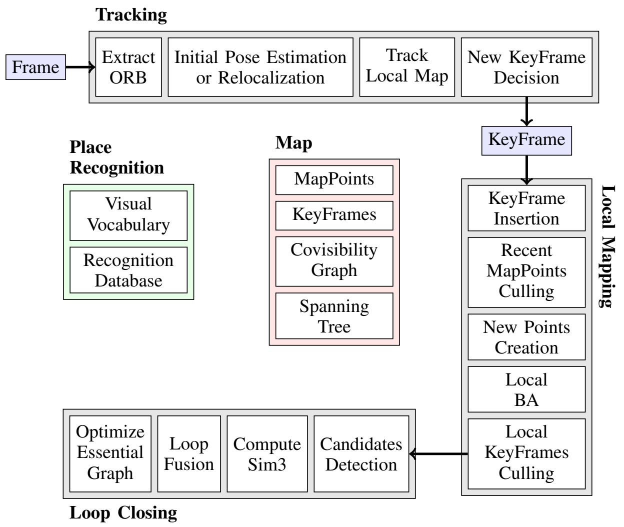

Fig. 1. The architecture of ORB-SLAM 2 system. ORB SLAM 2 runs on three threads parallel to each other. The *Tracking* thread does the real-time pose estimation, the *Local Mapping* thread creates new map points and optimize the local map and the *Loop Closing* thread tries to find loops in the odometry and fixes it.

ORB-SLAM applies ORB feature detection as it provides rotation and scale invariance and it is fast enough to maintain real-time performance while it is suitable for both large-scale (i.e. distant frames) and small-scale (i.e. subsequent frames) matching. The great innovation in ORB SLAM is that it uses ORB for every part of the process: tracking, mapping and loop closing are executed on ORB features. The ORB-SLAM system provides visual odometry as follows:

1) The ORB-SLAM starts with an automatic initialization method to retrieve the initial pose and map by extracting the ORB features, matching them and computing corresponding fundamental matrix and homography (i.e. the two dimensional projective transformation) in the same time. It computes a score to both the homography and the fundamental matrix as:

$$S_M = \sum_i \left(\rho_M\left(d^2_{cr}(\mathbf{x}^i_c, \mathbf{x}^i_r, M)\right) + \rho_M\left(d^2_{rc}(\mathbf{x}^i_c, \mathbf{x}^i_r, M)\right)\right)$$

$$\rho_M(d^2) = \begin{cases} \Gamma - d^2 & \text{if} \quad d^2 < T_M \\ 0 & \text{if} \quad d^2 \geq T_M \end{cases} \tag{9}$$

where M is the model (H for homography and F for fundamental matrix), d^2_{cr} and d^2_{rc} are the symmetric transfer errors, T_M is the outlier rejection threshold based on the χ^2 test at 95% ($T_H = 5.99$, $T_F = 3.84$, assuming a standard deviation of 1 pixel in the measurement error). Γ is a score compensating constant. ORB-SLAM recover initial pose and map from homography, if

$$\frac{S_H}{S_H + S_F} > 0.45 \tag{10}$$

otherwise it uses the fundamental matrix. After recovering pose and map it starts a non-linear optimization (bundle adjustment) to refine the initial model.

2) After map initialization, tracking tries to match ORB features of the current frame to the ORB features of the previous frame through a guided search employing a constant velocity model. The pose is then refined by non-linear optimization. After pose estimation, ORB-SLAM tries to reproject the map onto the frame, recovering more feature matches. The last step is the keyframe decision which judges that the current frame should be passed to the local mapping thread. This step utilizes a couple of complex conditions.
3) Parallel to tracking, every keyframe is processed to provide a consistent map that is able to refine the tracking process and provides input to loop closing. Briefly, local mapping triangulates new point candidates having passed a restrictive map point culling test and uses local bundle adjustment to minimize reprojection error. To maintain compact reconstruction ORB-SLAM removes redundant keyframes.
4) Loop closing happens parallel to tracking and mapping and uses bag of words representation and co-visibility information to detect loop candidates [27]. In case of loop detection it computes the similarity transformation accumulated while tracking to distributes the error along the whole path.

ORB-SLAM has been proven to be a robust and accurate solution even in large-scale areas and can successfully track ad-hoc movements while providing stable map initialization in case of a lost track. ORB-SLAM requires at least 20 frames per second to work well which can hardly be satisfied using ORB feature detection on embedded devices like smartphones without exploiting massive GPU calculations.

IV. Direct solutions

The principle behind direct solutions states that using the image intensities results in better odometry accuracy because it exploits all the information embedded in the frames while feature based solutions discard image information over feature points. The most important term of direct solutions is the *photo-consistency* discussed in the next section.

A. Photo-consistency theory

From a mathematical perspective, photo-consistency means that given two images I_1 and I_2, an observed point $\mathbf{p}$ by the two cameras yields to the same brightness in both images [28]:

$$I_1(\mathbf{u}) = I_2(\tau(\xi, \mathbf{u})) \tag{11}$$

where $\mathbf{u}$ is the projection of $\mathbf{p}$, $\tau(\cdot)$ is the *warping* function, which depends on $\pi(\cdot)$ (see Eq. 1). The warping function maps a pixel coordinate from the first image to the second one given the camera motion ξ. Here, the motion ξ can be represented in any minimal representation (e.g. twist coordinates). Given the residual function for any $\mathbf{u}$ point in the Ω image domain

$$r(\xi, \mathbf{u}) = I_2(\tau(\xi, \mathbf{u})) - I_1(\mathbf{u}) \tag{12}$$

which depends on ξ and assuming independent pixel noise, the maximum likelihood (ML) solution is a classical minimization problem:

$$\xi_{ML} = \arg\min_{\xi} \int_{\Omega} r^2(\xi, \mathbf{u})\, d\mathbf{u} \tag{13}$$

The problem is obviously non-linear so the common solution is to run iterative minimization algorithms like Newton-Gauss method over a discretized image. To speed up the integration process, the integration can be run over a couple of selected patches instead of every pixels in the images.

B. DTAM

Dense Tracking and Mapping (DTAM) uses the photo-consistency theory in a special way to provide dense maps and real-time visual odometry [29]. The main idea behind dense mapping is to sum the photometric error along a ray from the camera center and find the d distance which minimize the sum thus finding the depth parameter for that pixel. The summing is made along a couple of short baseline frames $m \in I(r)$ for a r reference frame:

$$C_r(\mathbf{u}, d) = \frac{1}{|I(r)|} \sum_{m \in I(r)} \|r_r(I_m, \mathbf{u}, d)\|_1 \tag{14}$$

where $\|\cdot\|_1$ is the $L1$ norm and the photometric error is

$$r_r(I_m, \mathbf{u}, d) = I_m(\tau(d, \mathbf{u}_i)) - I_r(\mathbf{u}_i) \tag{15}$$

Note that the only change in the equation is the parameter d. DTAM showed that minimizing the cost yields to a correct estimation of pixel depth which can be used to build dense maps.

The tracking part of the DTAM solution provides 6dof estimation and basically happens the same way as shown in Eq. 13 with a couple of extensions to provide robust tracking with occlusion detection.

The DTAM is robust and accurate visual odometry solution with excellent mapping capabilities. It is not only capable of handling occlusions but can track the movements even in case of total lost in focus and keep on tracking even for fast and random movements. The only drawback of the solution is that real-time performance requires huge computing capacity and massive GPU utilization.

C. LSD-SLAM

Large-Scale Direct Monocular SLAM (LSD-SLAM) uses direct methods combined with a probabilistic approach to track camera movements and build dense maps real-time [30]. The LSD-SLAM has a scale-aware image alignment algorithm which directly estimates the similarity transformation between two keyframes to provide scale consistent maps and odometry.

The main process of the LSD-SLAM is as follows: at every new frame it tries to estimate the movement relative to the current keyframe then it decides whether the actual keyframe should be replaced by the new frame. In case of replacement it initializes a new depth map otherwise it propagates the depth map of the current keyframe. At every keyframe replacement LSD-SLAM runs a map optimization which is essential to create accurate dense maps.

LSD-SLAM uses image patches to recover pose around pixels with large intensity gradients. The tracking process is composed of two steps: estimation of rigid body transformation and depth map propagation. The former one is a weighted optimization of the variance-normalized photometric error

$$E_p(\xi_j) = \sum_{p \in \omega_{D_i}} \left\| \frac{r_p^2(\mathbf{u}, \xi_j)}{\sigma^2_{r_p(\mathbf{u}, \xi_j)}} \right\|_\delta \tag{16}$$

for an existing keyframe and the new frame I_j. In the cost function $r_p(\cdot)$ is the photometric error, σ_{r_p} is the variance of the photometric error and $\|\cdot\|_\delta$ expresses the Huber-norm. Apart from normalization by variance this is a classical photometric error based odometry solution as in Eq. 13.

The biggest difference to other direct solutions is that the depth information for a keyframe is calculated in a probabilistic way, i.e. it is refined as new frames received. An inverse depth map and a depth map variance map is assigned to every keyframe selected by the LSD-SLAM process. The depth map is initialized with the depth map of the previous keyframe or with a random depth map if no keyframe exists. For each new frame the depth map is propagated as in [31], namely if the inverse depth for a pixel was d_0 then for the new frame it is approximated as

$$\begin{aligned} d_1 &= (d_0^{-1} - t_z)^{-}1 \\ \sigma^2_{d_1} &= \left(\frac{d_1}{d_0}\right)^4 \sigma^2_{d_0} + \sigma^2_p \end{aligned} \tag{17}$$

where σ_p is the prediction uncertainty and t_z is the camera translation along the optical axis.

LSD-SLAM also contains solution for the problem of scale-drift over long trajectories, which is the major source of error in the family of SLAM solutions. LSD-SLAM thus aligns two differently scaled keyframes by incorporating the depth residual into the error function shown above. This method penalizes deviations in inverse depth between keyframes and helps to estimate the scaled transformation between them.

D. SVO

The Fast Semi-Direct Monocular Odometry (SVO) is a great example of a hybrid solution for visual odometry using direct and feature based algorithms as well [32]. The SVO combines the probabilistic approach of depth map with the computationally attractive feature based concept as the name suggests providing real-time odometry and sparse mapping.

The basic process of SVO is tracking and mapping on parallel threads, i.e. calculating the movement trajectory at each frame real-time and select keyframes which can be used for mapping on the mapping thread. As the mapping thread uses features, bundle adjustment can be used to minimize reprojection error and construct accurate maps.

The tracking thread projects the 3D points of the map onto the new frame and uses the vicinity of the projected points in the image to estimate the motion relative the previous frame by photometric error optimization. The pose is refined by aligning the frame to the whole map (using Lucas-Kanade algorithm [33]) then by local bundle adjustment to apply the epipolar constraints.

The unique solution of the SVO is the fact that no depth map is computed but for each feature point on a keyframe a depth-filter is assigned which estimates the feature depth in a probabilistic way. First, the mapping thread decides the new frame to be a keyframe or not. Feature extraction is executed on new keyframes and to each feature is assigned a freshly initialized depth-filter. On interframes (i.e. not keyframes) the depth-filters for the features are updated until they converge to the estimated value and the variance is small enough. Converged depth filter are converted to map points by triangulation.

Thanks to the feature based mapping process SVO has proven to be faster than other direct solutions however the result is a sparse map rather then a dense one. The depth filters are a capable of detecting outlier measurement and the map is always consistent and correct because triangulation happens only when the filters converged. As the SVO uses couple of small patches around features to estimate motion it is capable of running real-time as well.

V. FILTER-BASED SOLUTIONS

In the real-time applications the relative pose estimation should be seamless, which can not be guaranteed just by image processing. To overcome this problem motion models are introduced to estimate the camera state between pose estimations. One on the most reliable solution is demonstrated as the MonoSLAM [34] for smooth camera motion in a desk-scale local environment.

In indoor application the most reasonable choice for motion estimation is to combine measurements of IMU, gyroscope and accelerometer with the measurements from projective camera images of the environment.

The filter based family of visual odometry algorithms fuses inertial IMU measurements with visual feature observations. In these methods, the current IMU poses and positions of visual landmarks are jointly estimated. These approaches share the same basic principles with camera-only localization based on bundle-adjustment. These solutions in the most cases integrate inertial data from IMU and pose estimations from camera measurements. These combined techniques are characterized as *loosely coupled* and *tightly coupled* systems. In loosely coupled systems [35] [36] [37] inertial and camera measurements are processed separately before being fused as a single relative pose estimate, while tightly coupled systems process all the information together [38] [39]. However loosely coupled systems limit computational complexity, in the following we focus on tightly coupled techniques due to its ability to reach higher consistency between camera poses and map of landmarks.

A. Theory

The original relative pose estimation problem is hard due to its nature. The algorithms use a map containing visual information to localize, while relative pose is necessary to construct and update the visual map. The problem becomes even harder to solve if we consider the noise of the sensor measurements. Various probabilistic methods are used to deal with the uncertainty introduced by measurement noise, Extended Kalman Filter (EKF), Particle Filter (PF), which are all based on Bayesian technique for random value estimation of system state parameters, including the camera location and orientation at a discrete time ($\mathbf{x}_k$) based on observations ($\mathbf{z}_k = \{\mathbf{z}_{ik}\}$) from a given location on the environment landmarks, in other words the map points ($\mathbf{m} = \{\mathbf{m}_1, \mathbf{m}_2, ..., \mathbf{m}_n\} = \mathbf{m}_{1:n}$), while the camera location is controlled independently of the $\mathbf{u}_k$ system state (see Fig. 2). The problem of relative pose estimation is given then in the probabilistic form as follows. [3]

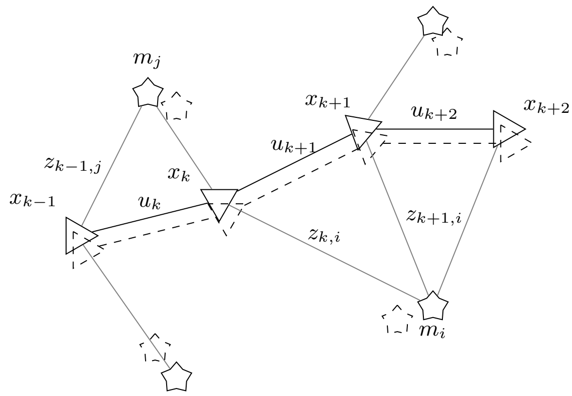

Fig. 2. The probabilistic SLAM problem. The triangles show the robot poses while stars represent landmarks. We depicted the true values with solid lines and the estimated values with dashed lines. The observations always made between the true location and the true landmark position.

$$P(\mathbf{x}_k, \mathbf{m}|\mathbf{z}_{0:k}, \mathbf{u}_{0:k}, \mathbf{x}_0) \tag{18}$$

The calculation of position probability distribution is done iteratively starting from $P(\mathbf{x}_{k-1}, \mathbf{m}|\mathbf{z}_{1:k-1}, \mathbf{u}_{1:k-1}, \mathbf{x}_0)$ with input of the actual control $\mathbf{u}_k$ and measurement $\mathbf{z}_k$ using Bayesian Theorem. The computation from one side requires the *state transition* or *motion model* for the camera that describes the new state regarding the control input.

$$P(\mathbf{x}_k|\mathbf{x}_{k-1}, \mathbf{u}_k) \tag{19}$$

Secondly the *observation* model describes the probability of making and observation $\mathbf{z}_k$, when a camera and landmark locations are known.

$$P(\mathbf{z}_k|\mathbf{x}_k, \mathbf{m}) \tag{20}$$

The iteration is then implemented in a standard two-step recursive process. The first step is the *time update* that *propagates* state in time.

$$P(\mathbf{x}_k, \mathbf{m}|\mathbf{z}_{0:k-1}, \mathbf{u}_{0:k}, \mathbf{x}_0) = \int P(\mathbf{x}_k|\mathbf{x}_{k-1}, \mathbf{u}_k) \cdot P(\mathbf{x}_{k-1}, \mathbf{m}|\mathbf{z}_{0:k-1}, \mathbf{u}_{0:k-1}, \mathbf{x}_0)\, \mathrm{d}\mathbf{x}_{k-1} \tag{21}$$

The second step conveys the *measurement* or *update*, when based on the state dependent measurements *correction* is done on the actual state.

$$P(\mathbf{x}_k, \mathbf{m}|\mathbf{z}_{0:k}, \mathbf{u}_{0:k}, \mathbf{x}_0) = \frac{P(\mathbf{z}_k|\mathbf{x}_k, \mathbf{m})P(\mathbf{x}_k, \mathbf{m}|\mathbf{z}_{0:k-1}, \mathbf{u}_{0:k}, \mathbf{x}_0)}{P(\mathbf{z}_k|\mathbf{z}_{0:k-1}, \mathbf{u}_{0:k})} \quad (22)$$

B. The IMU model

In indoor applications practically gyroscope and accelerometer measurements can be used to determine actual relative pose, and in filter algorithms for filter state propagation. All these measurements are stressed with local measurement noise, distortion and biases. The accelerometer measures actual acceleration ($\mathbf{a}_{m,\mathcal{I}} \in \mathbb{R}^3$) in the IMU orientation frame ($\mathcal{I}$), and its model can be formulated as follows.

$$\mathbf{a}_{m,\mathcal{I}}(t) = \mathbf{T}_a \mathbf{R}_{\mathcal{I}\mathcal{G}}(t)(\mathbf{a}_{\mathcal{G}}(t) - \mathbf{g}) + \mathbf{a}_b(t) + \mathbf{a}_n(t) \quad (23)$$

, where $\mathbf{a}_{\mathcal{G}}$ is the real acceleration in the global orientation frame, $\mathbf{g}$ is the gravity acceleration. $\mathbf{R}_{\mathcal{I}\mathcal{G}}$ represents the rotational transformation between the IMU frame ($\mathcal{I}$) and the global frame ($\mathcal{G}$), while $\mathbf{T}_a$ shape matrix comprises the gyroscope axis misalignments and scale errors. The measurement noise $\mathbf{a}_n$ is modelled as a zero mean Gaussian random variable, $\mathbf{a}_n \sim \mathcal{N}(\mathbf{0}, \mathbf{N}_a)$, and the bias $\mathbf{a}_b$ changes over the time and is modelled as a random walk process driven by its own noise vector $\mathbf{a}_{wn} \sim \mathcal{N}(\mathbf{0}, \mathbf{N}_{wa})$

Regarding the gyroscope, it measures rotational velocity ($\boldsymbol{\omega}_{m,\mathcal{I}} \in \mathbb{R}^3$) in the IMU orientation frame, its realistic model looks like the following:

$$\boldsymbol{\omega}_{m,\mathcal{I}}(t) = \mathbf{T}_g \boldsymbol{\omega}_{\mathcal{I}}(t) + \mathbf{T}_s \mathbf{a}_{\mathcal{I}}(t) + \boldsymbol{\omega}_b(t) + \boldsymbol{\omega}_n(t) \quad (24)$$

, where $\boldsymbol{\omega}_{\mathcal{I}}$ is the real rotational velocity in the IMU orientation frame, $\mathbf{T}_g$ is the shape matrix, while $\mathbf{T}_s \mathbf{a}_{\mathcal{I}}$ represents the influence of the acceleration to the the rotational velocity.

In practice, due to their insignificant effects scale and misalignment and acceleration influence is considered idealistic ($\mathbf{T}_a = \mathbf{T}_g = \mathbf{I}, \mathbf{T}_s = \mathbf{0}$).

C. Extended Kalman Filter (EKF)

The Bayesian technique can be solved by EKF, where the motion or state transition model (Eq. 19) is formalized by the following relation.

$$\mathbf{x}_k = \mathbf{f}(\mathbf{x}_{k-1}, \mathbf{u}_k) + \mathbf{w}_k \quad (25)$$

where $\mathbf{f}$ function models the vehicle kinematics in function of the actual state $\mathbf{x}_{k-1}$ and the actual control input $\mathbf{u}_k$ and $\mathbf{w}_k$ is an additive zero mean Gaussian noise with covariance $\mathbf{Q}_k$ ($\mathbf{w}_k \sim \mathcal{N}(\mathbf{0}, \mathbf{Q}_k)$).

On the other side EKF implements the generic observation model (Eq. 20) by the following equation.

$$\mathbf{z}_k = \mathbf{h}(\mathbf{x}_k, \mathbf{m}) + \mathbf{v}_k \quad (26)$$

where $\mathbf{h}$ function describes the relation between the actual state $\mathbf{x}_k$ and the map landmarks $\mathbf{m}$ with the projected point of landmark $\mathbf{z}_k$. The $\mathbf{v}_k$ is again an additive zero mean Gaussian error of observation with covariance $\mathbf{R}$ ($\mathbf{v}_k \sim \mathcal{N}(\mathbf{0}, \mathbf{R})$).

The system state vector of filter-based visual odometry solutions can be divided into the part related to the motion estimation ($\mathbf{x}_{IMU}$) and the auxiliary section related to the observation model related to the certain solution ($\mathbf{x}_{aux}$).

$$\mathbf{x} = [\mathbf{x}_{IMU}, \mathbf{x}_{aux}] \quad (27)$$

The related state covariance matrix ($\mathbf{P}_k$) can also be divided into parts related to the motion model ($\mathbf{P}_{IMU}$), the observation model ($\mathbf{P}_{aux}$), and the part describes the relation between these parameters ($\mathbf{P}_{IMU,aux}$).

$$\mathbf{P}_k = \begin{bmatrix} \mathbf{P}_{IMU} & \mathbf{P}_{IMU,aux} \\ \mathbf{P}_{IMU,aux}^T & \mathbf{P}_{aux} \end{bmatrix} \quad (28)$$

During the time update the state vector estimate and related covariance matrix is updated according to the following equations.

$$\begin{aligned} \hat{x} &\leftarrow \mathbf{f}(\hat{x}, \mathbf{u}) \\ \mathbf{P} &\leftarrow \mathbf{F}\mathbf{P}\mathbf{F}^T + \mathbf{Q} \end{aligned} \quad (29)$$

where the $\mathbf{F}$ is the Jacobian of f function and evaluated at the estimate $\hat{x}_k$, thus $\mathbf{F} = \frac{\partial \mathbf{f}(\hat{x}, \mathbf{u})}{\partial \mathbf{x}}|_{\hat{x}_k}$.

Based on the visual observations the correction is formulated in the following equations, that describes the residual, the Kalman gain, respectively.

$$\begin{aligned} \mathbf{r} &= \mathbf{z} - \mathbf{h}(\mathbf{x}) \\ \mathbf{K} &= \mathbf{P}\mathbf{H}^T(\mathbf{H}\mathbf{P}\mathbf{H}^T + \mathbf{R})^{-1} \end{aligned} \quad (30)$$

According to the residual and the Kalman gain the estimated state and covariance matrix updates are defined as the followings.

$$\begin{aligned} \hat{\mathbf{x}} &\leftarrow \hat{\mathbf{x}} + \mathbf{K}\mathbf{r} \\ \mathbf{P} &\leftarrow (\mathbf{I} - \mathbf{K}\mathbf{H})\mathbf{P} \end{aligned} \quad (31)$$

Considering the 6dof kinematic properties of the smartphone the application requires from the filter state to store actual orientation, position, velocity and the gyroscope and accelerometer bias parameters. According to this consideration the kinematic part of the filter state is defined by the following vector.

$$\mathbf{x} = [\mathbf{q}_{\mathcal{G}\mathcal{I}}, \mathbf{p}_{\mathcal{I},\mathcal{G}}, \mathbf{v}_{\mathcal{I},\mathcal{G}}, \boldsymbol{\omega}_b, \mathbf{a}_b]^T \quad (32)$$

During the state propagation using the gyroscope-accelerometer measurement pair the nominal values of kinetic part of the state should follow the kinetic equations below.

$$\begin{aligned} \dot{\mathbf{q}}_{\mathcal{G}\mathcal{I}} &= \frac{1}{2}\mathbf{q}_{\mathcal{G}\mathcal{I}} \otimes (\boldsymbol{\omega}_m - \boldsymbol{\omega}_b), \quad \dot{\mathbf{p}}_{\mathcal{I},\mathcal{G}} = \mathbf{v}_{\mathcal{I},\mathcal{G}}, \\ \dot{\mathbf{v}}_{\mathcal{I},\mathcal{G}} &= \mathbf{R}_{\mathcal{G}\mathcal{I}}(\mathbf{a}_m - \mathbf{a}_b) + \mathbf{g}, \quad \dot{\boldsymbol{\omega}}_b = \mathbf{0}, \quad \dot{\mathbf{a}}_b = \mathbf{0} \end{aligned} \quad (33)$$

D. Particle Filter

The bayesian propagation and measurement equations (see Eq. 22 and Eq. 21) cannot be solved in a closed form for the SLAM problem. For Gaussian-distribution the solution can be approximated with various Kalman-filters but the exact solution for strongly non-linear models can only be found by numerical integration.

Given a $\mathbf{g}(\mathbf{x}) : \mathbb{R}^n \longrightarrow \mathbb{R}^m$ function, the expectation over a posterior distribution:

$$E[\mathbf{g}(\mathbf{x})|\mathbf{z}_{1:k}] = \int \mathbf{g}(\mathbf{x}) P(\mathbf{x}|\mathbf{z}_{1:k})\, d\mathbf{x} \tag{34}$$

can be approximated by drawing N independent random samples $\mathbf{x}^{(i)}$ form the $p(\mathbf{x}|\mathbf{z}_{1:k})$ distribution:

$$E[\mathbf{g}(\mathbf{x})|\mathbf{z}_{1:k}] \approx \frac{1}{N}\sum_{i=1}^{N} \mathbf{g}(\mathbf{x}^{(i)}) \tag{35}$$

This type of numerical calculation of integrals is called Monte Carlo method [40]. However, in case of the Bayesian models it is not possible to draw samples from $P(\mathbf{x}|\mathbf{z}_{1:k})$, so we need to approximate it someway. The solution is to find an approximate importance distribution $\Pi(\mathbf{x}|\mathbf{z}_{1:k})$ from which it is easy to draw samples. These kind of techniques are called importance sampling methods. *Particle filter* is the method of using *sequential importance resampling* algorithm. This forms the posterior distribution with a couple of $w_k^{(i)}$ weights.

$$p(\mathbf{x}_k|\mathbf{z}_{1:k}) \approx \sum_{i=1}^{N} w_k^{(i)} \delta(\mathbf{x}_k - \mathbf{x}_k^{(i)}) \tag{36}$$

where $\delta(\cdot)$ is the Dirac-delta.

E. Solutions

1) EKF-SLAM: In EKF-SLAM algorithms, the filter state vector contains the current IMU state $\mathbf{x}_{IMU}$ and the observed feature 3D positions ($\mathbf{p}_{f_i}$). Thus the filter state vector is defined as follows.

$$\mathbf{x}_k = [\mathbf{x}_{IMU,k}, \mathbf{p}_{f_{1,k}}^T ... \mathbf{p}_{f_{n,k}}^T]^T \tag{37}$$

The 3D features can be parametrized traditionally using (x, y, z) coordinates, the anchored homogeneous parametrization [41], and the inverse-depth parametrization [42]. Although the former one is straightforward, the latter two increases the consistency and accuracy.

The EKF-SLAM uses the ”standard” propagation method of states ($\mathbf{x}_k$) and covariance matrix ($\mathbf{P}_k$) based on the IMU inertial measurements as described above, while the *update process* is calculated on the actual image features. Assuming a calibrated perspective camera, the observation of feature i on the actual image at time step k is expressed by the following equation describing the actual observation.

$$\mathbf{z}_{i,k} = \mathbf{h}(\mathbf{x}_{IMU,k}, \mathbf{p}_{f_{i,k}}) = \frac{1}{z_{f_i,\mathcal{C}_k}} \begin{bmatrix} x_{f_i,\mathcal{C}_k} \\ y_{f_i,\mathcal{C}_k} \end{bmatrix} + \mathbf{n}_{i,k} \tag{38}$$

where $\mathbf{n}_{i,k}$ is the measurement noise, and the $\mathbf{p}_{f_i,\mathcal{C}_k} = [x_{f_i,\mathcal{C}_k}, y_{f_i,\mathcal{C}_k}, z_{f_i,\mathcal{C}_k}]$ describes the observed feature position in the camera orientation frame $\mathcal{C}_k$, and this position is described by the following equation and the $\mathbf{p}_{\mathcal{I},\mathcal{C}}$ and $\mathbf{R}_{\mathcal{CI}}$ are the fixed position and rotation transformation between the IMU ($\mathcal{I}$) and the camera ($\mathcal{C}$) frames.

$$\mathbf{p}_{f_i,\mathcal{C}_k} = \mathbf{R}_{\mathcal{CI}} \mathbf{R}_{\mathcal{I}_k \mathcal{G}} (\mathbf{p}_{f_i,\mathcal{G}} - \mathbf{p}_{\mathcal{I}_k,\mathcal{G}}) + \mathbf{p}_{\mathcal{I},\mathcal{C}} \tag{39}$$

Assuming that the actual position of the IMU frame is $\mathbf{p}_{\mathcal{I}_k,\mathcal{G}}$ EKF-SLAM defines a residual as the difference between the real observation $\mathbf{z}_{i,k}$ of the feature i and the projection of the estimated feature position ($\hat{\mathbf{p}}_{f_i,\mathcal{C}_k}$), and linearizes it around the actual state ($\hat{\mathbf{x}}_{IMU,k}$) as:

$$\mathbf{r}_{i,k} = \mathbf{z}_{i,k} - \mathbf{h}(\hat{\mathbf{x}}_{IMU,k}, \hat{\mathbf{p}}_{f_i,\mathcal{C}_k}) \simeq \mathbf{H}_{i,k}(\hat{\mathbf{x}}_k)\tilde{\mathbf{x}}_k + \mathbf{n}_{i,k} \tag{40}$$

The $\mathbf{H}_{i,k}(\hat{\mathbf{x}}_k)$ is the Jacobian matrix of $\mathbf{h}$ with respect to the actual filter state estimate ($\hat{\mathbf{x}}_k$).

When the $\mathbf{r}_{i,k}$ and $\mathbf{H}_{i,k}$ are computed the outlier detection is done using Mahalanobis gating. If the test succeeds, from the residual and observation Jacobian the Kalman gain and the innovation are computed according to the basic EKF rules (see Eqs. 31). For the Mahalanobis gating we compute the following:

$$\gamma_i = \mathbf{r}_i^T (\mathbf{H}_i \mathbf{P}_i \mathbf{H}_i^T + \sigma^2 \mathbf{I})^{-1} \mathbf{r}_i \tag{41}$$

Then it is compared to the threshold given by the 96 percent of the χ^2 distribution.

The observation update step requires that all landmarks and joint-covariance matrix must be updated every time an image is registered by the camera. Considering the complexity of the EKF-SLAM it is straightforward that the computational complexity is dominated by cubic to the actual number of the landmarks, thus the complexity is $\mathcal{O}(n^2)$. In practice the actual map can consists of thousands of features, thus the EKF-SLAM becomes computationally intractable for large areas.

To provide first-aid to this problem Sola proposed a method, when the state and covariance matrices are updated by only the actual observed features. [43]

2) MSCKF: The fundamental advantage of filter-based algorithms is they account for the correlations that exist between the pose of the camera and the 3D position of the observed features. Besides, the main limitation is its high computational complexity, even when only hundreds of features are considered during calculations.

The motivation of Multi-State Constraint Filter (MSCKF) is the introduction of consecutive camera poses into the state instead of feature positions. This is first done by Nister [44], however this method does not incorporate inertial measurements. Sliding window-based solutions appear also in other solutions. [45]

Assuming that N of the camera poses are included in the EKF state vector at time step k, the MSCK state vector has the following form.

$$\mathbf{x}_k = [\mathbf{x}_{imu,k}, \mathbf{q}_{\mathcal{GC}_1}^T, \mathbf{p}_{\mathcal{C}_1,\mathcal{G}} ... \mathbf{q}_{\mathcal{GC}_N}^T, \mathbf{p}_{\mathcal{C}_N,\mathcal{G}}]^T \tag{42}$$

Since the *time update* is common for EKF-based pose estimation, the difference is maintained during the *measurement update* step. When new image arrives features are tracked among the last N camera poses. The update process considers each single feature f_j that has been observed from the set of N_j camera poses ($\mathbf{q}_{\mathcal{GC}_i}^T, \mathbf{p}_{\mathcal{C}_i,\mathcal{G}}$).

The estimated feature position $\hat{\mathbf{p}}_{f_j,\mathcal{G}}$ in the global frame is triangulated from camera poses using feature observations. Usually a least-square minimization is used with inverse-depth parametrization. [42] The residual $\mathbf{r}_j^{(j)}$ is then defined as the difference between re-projections of estimated feature $\hat{\mathbf{p}}_{f_j,\mathcal{G}}$ and the real feature observations.

$$\mathbf{r}_i^{(j)} = \mathbf{z}_i^{(j)} - \hat{\mathbf{z}}_i^{(j)} \tag{43}$$

On the other hand the residual can be approximated by linearising about the estimates of the camera poses and the feature positions, where $\mathbf{H}_{\mathbf{x}_i}$ and $\mathbf{H}_{f_j}^{(j)}$ are the Jacobians of the measurement $\mathbf{z}_i^{(j)}$ with respect to the state and the feature position, respectively. After stacking the residuals for each N_j measurements of the f_j features we get

$$\mathbf{r}^{(j)} \simeq \mathbf{H}_{\mathbf{x}}\tilde{\mathbf{x}} + \mathbf{H}_f^{(j)}\tilde{\mathbf{p}}_{f_j,\mathcal{G}} \quad (44)$$

Since the actual state estimate $\mathbf{x}$ is used for estimation of $\hat{\mathbf{p}}_{f_j,\mathcal{G}}$ the error of state $\tilde{\mathbf{x}}$ and of feature position $\tilde{\mathbf{p}}_{f_j,\mathcal{G}}$ are correlated. The solution of this problem is projecting $\mathbf{r}^{(j)}$ on the left null-space of the matrix $\mathbf{H}_f^{(j)}$. Define $\mathbf{A}^{(j)}$ as the unitary matrix the columns of which form the basis of the left null-space of $\mathbf{H}_f$, so we get:

$$\mathbf{r}_o^{(j)} \simeq \mathbf{A}^{(j)T}\mathbf{H}_{\mathbf{x}}^{(i)}\tilde{\mathbf{x}}^{(j)} + \mathbf{A}^{(j)T}\mathbf{n}^{(j)} = \mathbf{H}_o^{(j)}\tilde{\mathbf{x}}^{(j)} + \mathbf{n}_o^{(j)} \quad (45)$$

Also by stacking residuals into a single vector from observations from each f_j features, we obtain:

$$\mathbf{r}_o = \mathbf{H}_{\mathbf{x}}\tilde{\mathbf{x}} + \mathbf{n}_o \quad (46)$$

To reduce the computational complexity during update QR decomposition is applied on $\mathbf{H}_{\mathbf{x}}$ [46]. After determining the $\mathbf{T}_H$ upper triangular matrix and its corresponding unitary matrix whose columns form bases for the rand and null-space of $\mathbf{H}_{\mathbf{x}}$, $\mathbf{Q}_1$, the residual is then reformulated as the following:

$$\mathbf{r}_n = \mathbf{Q}_1^T\mathbf{r}_o = \mathbf{T}_H\tilde{\mathbf{x}} + \mathbf{n}_n \quad (47)$$

Based on the above measures, the residual $\mathbf{r}_n$ and the measurement Jacobian $\mathbf{T}_H$ the basic EKF update is used (see Eg. 31).

The correct co-operation between image based relative observations and inertial measurements requires to exactly know the transformation between camera and IMU orientation frames. In most of the solutions this transformation assumed to be known exactly, while EKF is appropriate also for the estimation of these parameters. The MSCKF 2.0 [46] introduces these parameters $(\mathbf{q}_{IC}, \mathbf{p}_{C,I})$ into the state. Besides, global orientation errors are considered and an improved linearizion and calculation of Jacobians are provided to improve the observability and in increase accuracy and stability.

The MSCKF model later is extended with estimation of rolling shutter camera properties [47] and temporal calibration [48], while algorithm is provided for on-line self-calibration [49], as well.

Regarding the computational complexity it is easy to realize that instead of the EKF-SLAM the complexity basically depends more on the registered camera states than the observed number of features. However the calculation of $\mathbf{T}_H$ depends on the number of features ($\sim d$) and the columns of the $\mathbf{Q}_1$ (r). The other crucial factor is determined by the computation of covariance matrix update. The cost of the MSCKF update is then calculated by $max\{\mathcal{O}(r^2d), \mathcal{O}(m^3))\}$, where m is the size of the state vector.

One can see that since MSCKF uses sliding window for camera states, tracked features can be observed only for a time limited to the window size. To overcome this limitation the authors designed a hybrid MSCKF-EKF SLAM solution, where MSCKF is applied only for short, while long features are inserted into the state vector. [50]

3) FastSLAM: The FastSLAM implements PF method, however the high dimensional state-space of the SLAM problem makes it computationally infeasible to apply particle filters directly on the Bayesian-equations. FastSLAM solves this problem by applying a factorization to the posterior distribution as follows [51]:

$$p(\mathbf{x}_{1:k}, \mathbf{m}|\mathbf{z}_{0:k}, \mathbf{u}_{0:k}, \mathbf{x}_0) = p(\mathbf{x}_{1:k}|\mathbf{z}_{0:k}, \mathbf{u}_{0:k}, \mathbf{x}_0)\cdot \prod_k p(\mathbf{m}_k|\mathbf{x}_{1:k}, \mathbf{z}_{0:k}, \mathbf{u}_{0:k}, \mathbf{x}_0) \quad (48)$$

The estimation thus can be done in two steps: first we estimate the posterior of the path trajectories then – based on the trajectory estimated – we estimate the locations of the K landmarks independently. The path estimation is done by a modified particle estimator using Monte Carlo method, while the estimation of the landmarks is achieved by Kalman-filters. Because landmarks are conditioned on the path estimation if M particle is used to estimate the trajectory then KM two dimensional Kalman-filter is required to estimate the landmarks.

FastSLAM runs time linear in the number of landmarks, however, the implementation of FastSLAM uses a tree representation of particles to run in $\mathcal{O}(M \log K)$. This way the resampling of particles can happen much faster than implemented naively.

The FastSLAM can handle huge amounts of landmarks – as extensive simulation has shown – and is at least as accurate as EKF-SLAM. However, the biggest problem of FastSLAM is the inability to forget the past (i.e. the pose and measurement history) and this way the statistical accuracy is lost [52].

FastSLAM has a more efficient extension called FastSLAM 2.0 which uses another proposal distribution including the current landmark observations and this way calculating the importance weights differently [53].

VI. IMPLEMENTATION ASPECTS

It is essential for visual odometry and SLAM algorithms to run real-time. Recent smartphones are equipped with a considerable amount of resources, like multiple cores of CPU and GPU. To face to the real-time requirements by utilizing parallel resources, some algorithms decouple real-time and background tasks. The computational burden is still really high for embedded devices. Fortunately, these algorithms give way to a lot of parallelization opportunities to speed up computations.

The feature extraction is also much faster if done parallel, e.g. SiftGPU reported to extract SIFT features at 27 FPS on a nVidia 8800GTX card [54]. The widespread OpenCV[1] library has also GPU support for various algorithms using CUDA and OpenCL. Not only feature detection and extraction but bundle adjustment can be parallelized to be ca. 30 times faster than native implementations such as the Multicore Bundle Adjustment project shows [55].

[1]OpenCV can be found at http://opencv.org

VII. EVALUATION

Beside the solutions described in this work, a huge amount of implementations are available. For the prudent comparison of the methods, algorithms and real implementations, widely known datasets are used. These datasets provide huge amount of video frames of different trajectories with ground truth, containing mainly grayscale and RGB images but often RGB-D and laser data is accessible. The most widely used datasets are the KITTI dataset [56], the RGB-D dataset [57] and New College Data Set [58], from those the KITTI odometry dataset consists of 22 stereo sequences (which can also be used as a monocular data) and a comprehensive evaluation of different SLAM methods listing accuracy and speed.

Regarding the KITTI dataset a huge list about the performance evaluation of available implementations is published at http://www.cvlibs.net/datasets/kitti/eval_odometry.php.

VIII. CONCLUSION

A huge variety of algorithms and solutions are currently available to tackle the strict requirements of the accurate and real time visual indoor positioning, that augmented reality-based applications demand. These algorithms build on the results of research work on computer vision from the last decades which went through a significant evolution, from SfM to the real-time SLAM approaches. However to face the real-time requirements, filter-based solutions tightly coupling inertial measurements with visual odometry are emerging. Through embedding inertial measurements from IMU for motion estimation to the projective geometry principles, these approaches are promising for the future implementations, however they suffer from the long-lasting state parameter estimations.

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Important Dates

28 November 2016
Full paper submission

30 January 2017
Paper acceptance notification

6 March 2017
Camera-ready papers and early registration

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- "State of the Art in Nanotechnology", by Prof. Stephen Goodnick, IEEE Fellow, Arizona State University, USA
- "What does European Energy Turnover (Energiewende) Mean for Small countries", Prof. Rafael Mihalic, Univ. of Ljubljana, Slovenia
- "Intelligent Vehicles", TBA
- "INDUSTRIE 4.0 — Smart Manufacturing ", TBA
- "Does DC Distribution Make Sense?", TBA

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- "Advanced Switching Based Systems" – Jun Zhao, Northeastern Univ., Shenyang, China

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- "Prospective of Nuclear Energy in Europe", Moderator: Prof. Nikola K. Popov, McMaster University, Ontario
- "Systems-of-Systems or Complex Systems Engineering?", Moderator: Jun Zhao, Northeastern Univ., Shenyang, China
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Sensors for automobiles and Upcoming Technologies

John Baekelmans — CTO, Internet of Everything (IoE) Solutions Group, Cisco, London, UK
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[11] Boggs, S.A. and Fujimoto, N., "Techniques and instrumentation for measurement of transients in gas-insulated switchgear," IEEE Transactions on Electrical Installation, vol. ET-19, no. 2, pp.87–92, April 1984.

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[26] Peck, R.B., Hanson, W.E., and Thornburn, T.H., Foundation Engineering, 2nd ed. New York: McGraw-Hill, 1972, pp.230–292.

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Purdue University, USA

Communications for the Smart Grid
Deepa Kundur, University of Toronto, Canada

Data Storage
Onur Ozan Koyluoglu,
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Next Generation Networking and Internet
Shiwen Mao, Auburn University, USA
Mahesh K. Marina, University of Edinburgh, UK
Sidi-Mohammed Senouci,
University of Bourgogne, France

Signal Processing for Communications
Michael Buehrer, Virginia Tech, USA
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Optical Networks and Systems
Grzegorz Danilewicz,
Poznan University of Technology, Poland
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Davide Dardari,
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Hämäläinen Jyri,
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Missouri University of Science and Technology, USA

Mobile and Wireless Networking
Mohammed Atiquzzaman,
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IEEE ICC 2017 will feature several prominent keynote speakers, major business and technology forums, and a large number of vendor exhibits. Submit your proposals to the IF&E Co-Chairs Luis M. Correia (luis.correia@inov.pt) and Jamshid Khun-Jush (khunjush@qti.qualcomm.com).

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Proposals are invited for half- or full-day tutorials in all communication and networking topics. For enquiries, please contact the Tutorials Program Co-Chairs Hanna Bogucka (hanna.bogucka@put.poznan.pl) and Luc Vandendorpe (luc.vandendorpe@uclouvain.be).

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Proposals are invited for half- or full-day workshops in all communication and networking topics. For enquiries, please contact the Workshops Program Co-Chairs Abbas Jamalipour (a.jamalipour@ieee.org) and Constantinos Papadias (cpap@ait.gr).

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IMPORTANT DATES

Paper Submission: 14 October 2016

Tutorial Proposals: 11 November 2016

IF&E Proposals: 11 November 2016

Workshop Proposals: 24 June 2016

Paper Acceptance Notification: 27 January 2017

Camera-Ready Papers Due: 24 February 2017

Full details of submission procedures are available at icc2017.ieee-icc.org

#IEEEICC17

SCIENTIFIC ASSOCIATION FOR INFOCOMMUNICATIONS

Who we are

Founded in 1949, the Scientific Association for Infocommunications (formerly known as Scientific Society for Telecommunications) is a voluntary and autonomous professional society of engineers and economists, researchers and businessmen, managers and educational, regulatory and other professionals working in the fields of telecommunications, broadcasting, electronics, information and media technologies in Hungary.

Besides its 1000 individual members, the Scientific Association for Infocommunications (in Hungarian: Hírközlési és Informatikai Tudományos Egyesület, HTE) has more than 60 corporate members as well. Among them there are large companies and small-and-medium enterprises with industrial, trade, service-providing, research and development activities, as well as educational institutions and research centers.

HTE is a Sister Society of the Institute of Electrical and Electronics Engineers, Inc. (IEEE) and the IEEE Communications Society.

What we do

HTE has a broad range of activities that aim to promote the convergence of information and communication technologies and the deployment of synergic applications and services, to broaden the knowledge and skills of our members, to facilitate the exchange of ideas and experiences, as well as to integrate and harmonize the professional opinions and standpoints derived from various group interests and market dynamics.

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- contribute to the analysis of technical, economic, and social questions related to our field of competence, and forward the synthesized opinion of our experts to scientific, legislative, industrial and educational organizations and institutions;
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- promote professional secondary and higher education and take active part in the development of professional education, teaching and training;
- establish and maintain relations with other domestic and foreign fellow associations, IEEE sister societies;
- award prizes for outstanding scientific, educational, managerial, commercial and/or societal activities and achievements in the fields of infocommunication.

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