Design and energy optimization of a multifunctional IoT solution for connected bikes

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***Abstract*—IoT systems face a severe energy autonomy challenge in keeping electronics alive without massive and heavy batteries, pressing for the development of efficient ultra low power architectures and energy harvesting solutions. In this paper we present a new IoT system designed for long-term tracking applications of personal vehicles and moving assets, such as bicycles and carts. The system integrates Cellular, GNSS and BLE communication technologies that enable the implementation of a wide set of geo-aware tracking and fitness monitoring applications. Power consumption minimization is one of the main goals and design challenges for the presented system. This paper focuses on methods and techniques for power consumption optimization at the hardware and software level. We present the design of a miniature kinetic energy harvesting solution and of system architectures for leakage currents minimization and ultra-low power consumption. Results obtained in both simulation and in-field experiments demonstrate high efficiency and performance of the proposed solution, resulting in energy neutral performance of continuous tracking task.**

I. Introduction

The IoT is a rapidly growing technological field with constantly expanding application scope. Smart vehicles and car-free urban mobility is one of the domains where IoT is envisioned to be ubiquitous. Government institutions and organizations around the world started to invest into more efficient urban transit facilities to provide sustainable emission-free transportation systems. New technologies allow conventional personal vehicles, such as bicycles, to be turned into globally connected systems that offer a wide range of benefits for users and riders, as well as for urban mobility in general. In recent years, the topic of connected vehicles and bikes has attracted attention from both research groups and industry. Recently, a set of research works [1]–[4] and products were proposed for bicycle applications. These aim to enhance riding experience, improve safety levels and address the needs that riders encounter every day, such as cycling routes navigation, fitness feedback, and theft protection. Almost all of the existing systems rely on primary or secondary battery sources that raise some serious challenges and require a careful design to provide an acceptable system lifetime. Thus, there is a demand for an efficient energy autonomous solution to keep electronics alive without bulky and heavy batteries.

In this paper we present a new multifunctional IoT system, designed specifically for long-term tracking operations in vehicle applications. The system consists of an embedded electronics device, an IoT cloud infrastructure, and a user mobile application. The embedded device integrates three communication technologies, i.e., Cellular 2/3G modem, Global Navigation Satellite System (GNSS) and Bluetooth Low Energy (BLE), that enable the implementation of a wide set of bike riding localization and fitness monitoring applications. The BLE connection is used for close proximity communication with the user's smartphone, while cellular and GNSS are utilized for global positioning and communication with a cloud server. A built-in Inertial Measurement Unit (IMU) enables the implementation of fitness related and dead-reckoning applications. The device features an ultra compact design, allowing it to be installed directly onto the frame of the bike, hiding it from hand and eye, enabling an efficient anti-theft solution. The collected data (e.g., geo-location, fitness profiling) are persistently stored in the cloud and can be accessed through a smartphone application and a web interface.

Minimizing power consumption for long-term operation is one of the main goals and design challenges for the presented system. Different approaches have been proposed over the years to address the high power consumption of GPS modems. One approach is to adapt and reduce the utilization of GPS modem exploiting historical user habits and data coming from other sensors [5] through machine learning schemes [6], [7]. For instance, in [8], the authors use the location-time history of the user to estimate velocity and adaptively turn on GPS only if the estimated uncertainty in position exceeds a threshold. In a similar fashion, authors of [9] implemented a middleware for Android platforms that exploits other sensors (e.g., accelerometer) to provide location information to apps running on the phone, and adaptively manage the GPS modem at the lower level. In this paper we investigate methods and techniques for power consumption optimization for a particular use case approached at the hardware level. In our previous work, we have analyzed different solutions that include extracting energy from the heat generated by system components [10]–[12], or tuning the sensor utilization patterns to reduce energy consumption [13]–[16]. In this paper, we present the system and power supply unit (PSU) architecture for ultra-low power consumption operation, and a kinetic energy harvesting solution for on-the-go battery recharge. At the software level a power- and trace-aware adaptive algorithm that provides an optimal balance between power consumption, input from an energy scavenging module, tracking accuracy and cloud data upload latency is presented. Simulation results and in-field experiments demonstrate the high efficiency of the proposed solution, enabling energy neutral operation of the tracking system, in specific configurations.

The paper is organized as follows. The IoT system architecture and the energy minimization strategy are presented in Section II. The energy harvesting solution architecture, experimental measurements and discussion on the system efficiency are given in Section III. Section IV discusses adaptive tracking approaches and their impact on energy budget and efficiency. Finally, Section V concludes the paper.

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II. IoT SYSTEM DESIGN

An efficient IoT system has to blend all elements of all levels, e.g., smart sensors, communication and data delivery, storage, online and mobile services, into a robust and efficient infrastructure that meets target application constrains and performance requirements. In this paper, we present a new IoT solution that implements such an infrastructure for a wide range of bicycle fitness profiling and geo-aware applications. The block diagram of the presented solution is shown in Figure 1. The system consists of embedded electronic devices installed on bikes, an IoT cloud server for data storage and analysis, and a mobile application for data accesses and visualization.

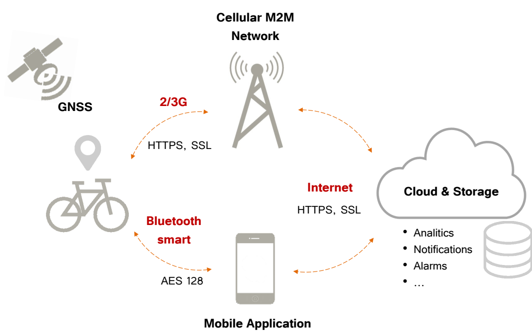

Fig. 1: IoT system block diagram

The main guiding requirements in designing the presented electronics solution include global connectivity, accurate geo-localization, energy efficient short range RF communication, low power consumption for long-term operation up to several months, and weight and size constraints. The embedded device is composed of multiple functional modules that include a main processing unit, a motion sensors unit, short-range and global communication modules, a low power GNSS chip, a power supply chain and a rechargeable Lithium Ion battery. The system block diagram is shown on Figure 2. The core component managing all the system operations is based on a SoC that integrates a low-power MCU and a BLE transceiver. A rich set of built-in peripheral components, such as UART, IIC, ADC and others, guarantees ease of integration and extension with external components and sensors. Three-axis ultra low power acceleration and gyro sensors interfaced with the MCU via IIC provide motion detection capabilities for system wake up operation, fitness monitoring and dead reckoning applications. The inertial sensors data is periodically analyzed to determine the system instantaneous state (velocity, inclination, etc.). Additionally, for the sake of power consumption reduction, the device is automatically put into the lowest power mode, consuming 25 μA, when no motion is detected for a predefined period of time. As soon as a motion series is detected, the accelerometer generates an interrupt to the MPU which then activates the main system functions.

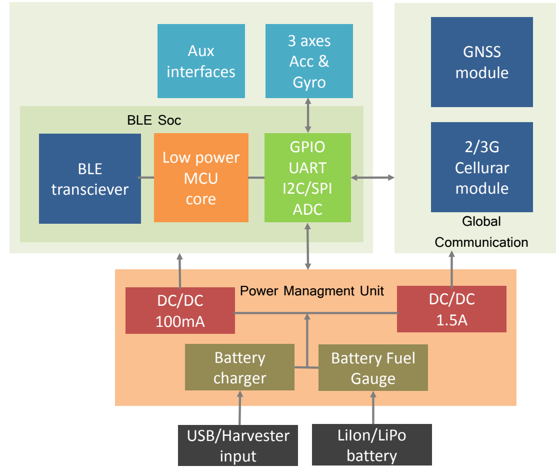

Fig. 2: IoT system architecture

BLE is a general purpose short range communication protocol introduced for a wide range of low power consumption applications. In the presented IoT system, the BLE interface is used for data exchange with a user smartphone, including the device configuration and real-time data visualization. In this case, the smartphone acts as a Central (or master) device while the embedded device operates in Peripheral (or slave) mode. The master initiates the connection and gets access to the Peripheral device Configuration Services and Characteristics. After the BLE connection is established, geo-localization data and communication with the cloud is delegated to the smartphone application. In the connected state, the embedded system consumes on average 120 μA, with a peak current draw of 14 mA during BLE data transmissions at 0 dBm output power level.

In case no smartphone is present in close proximity, and data is required to be sent to the server, the local Cellular and GNSS modules are activated, and possible compression of the data using compressing sampling [17], [18] will be implemented to reduce the payload. In the presented prototype, we utilized off-the-shelf modules that offer a compact, cost and quality effective solution suited for a wide range of telematics and M2M applications. The available serial interfaces provide ease of integration between the MCU, Cellular and GNSS modules. However, special attention is required in designing the power delivery chain for the communication modules. The cellular communication demands two to three orders of magnitude more power than the short range BLE connectivity. Additionally, the supply rail has to sustain current transmission pulses of 1 A to 1.5 A produced by the Cellular GPRS transmission operations. Thus, careful considerations for efficient load regulation and low-ripple are required. The cellular module current consumption depends on a number of factors such as the class supported by the module (Class 8 in our case), proximity to the cellular station, antenna design and even ambient conditions. In the presented case, the cellular module requires current in the range of 120 mA up to 1 A. The power requirements for GNSS are less strict, since the average consumption in active tracking mode is 16 mA and 1 mA in low power state. However, a careful PCB design of the power chains and proper grounding for EMI minimization, especially close to GNSS analog parts, are of high importance.

The power supply unit on the presented system consists of two functional sub-systems which include the power delivery rail and the battery management circuitry. Two high efficiency switching converters deliver power to two separate power branches: the low-power parts, i.e., the MCU and the sensory chains; and to the power demanding Cellular and GNSS modules. A two-branch power rail architecture enables a more

TABLE I: System current and power consumption

Component	Current Consumption	Power Consumption
BLE SoC		
Tx/Rx peak	14/12 mA	29.4/25 mW
BLE connection	100μA	210μW
Sleep	8μA	16μW
IMU sensors		
Active 100Hz	20μA	42μW
Off	2μA	4μW
Cellular 2G		
Tx/Rx peak	120 - 1000mA	450 - 3700mW
Active	13mA	50mW
Idle	1.1mA	4mW
GNSS		
Tracking mode	14mA	52mW
Idle	20μA	74μW
PMU		
Active	150μA	560μW
Idle	10μA	38μW

flexible power management by allowing us to completely disable the Cellular-GNSS part whenever cellular communication is not required. The power supply for GSM-GNSS is designed to deliver fixed 3.7 V with a supply current of up to 1.5 A.

The battery management sub-system is composed of a battery monitoring circuit and a battery charging module. The first module is based on a single fuel-gauge chip that incorporates methods for accurate measurement of the battery State of Charge (SoC). Along with SoC analysis, the fuel-gauge provides measurements on the battery voltage, the instantaneous temperature and the charge-discharge current. The fuel-gauge solution provides significant benefits over a standard ADC-MCU voltage-only analysis of the residual battery level. Accurate information about charge and capacity of the battery enables us to apply a more flexible power management strategy in energy sensitive and energy harvesting applications. The main power is delivered to the system by a single cell rechargeable LiIon 3.7 V battery. The battery charging is handled by a dedicated module taking 5 V DC sources, e.g., conventional USB or harvester modules. In order to increase robustness of the device, auxiliary elements for input supply over-voltage, inverse polarity and input ESD protection are incorporated. The assembled prototype of the presented system is shown on Figure 3. Table I summarizes current and power consumption values of all key system components.

III. Energy scavenging solution

The IoT device presented above features a set of ultra low-power components allowing long term operational autonomy. The actual system lifetime depends on a particular scheduling tracking algorithm for specific use case scenario. However, the autonomy of the presented system can be considerably extended by using on-the-go battery recharge, i.e., energy harvesting. In this section we investigate various energy harvesting solutions for the presented tracking system. The main guiding requirements for the designed energy harvesting subsystem include output power performance exceeding 10 mW, compact design and friction-free operation.

In a moving vehicle, energy can be harvested from different sources. Piezoelectric harvesters could be used to convert vibrations and user movements, while thermoelectric harvesters could be deployed where friction causes moving parts, like breaks, to heat. The energy density of such systems can be considered negligible (in the order of hundred of μW) with respect to the energy required by the tracking tasks. However, a large amount of kinetic energy is available in a moving object like a bike. This makes kinetic energy much more convenient than other sources such as photovoltaic [19], [20]. Based on available research work [21]–[25] electromagnetic vibration energy transducers working on the Faraday's law induction principles are considered as the most feasible solution that meets all of the above mentioned application requirements. In the following we present the design and characterization of different kinetic energy harvesting systems customized for vehicle tracking applications.

Single Coil - it consists of an induction coil, with ferromagnetic core, attached on the frame in close proximity to magnets placed on the rear wheel rim ($\approx 2 \div 3$ mm). 48 rectangular magnets (40x10x5 mm) are used to fill completely the rim (for a circumference of ≈ 2.13 m). Magnetic poles of contiguous magnets are interleaved (N-S-N-S-N. . .) to maximize magnetic field variation collected by the coil. In this configuration, the magnets rotate with the wheel and an alternating electromotive force is generated between the two terminals of the static coil.

Double Coil - using the very same magnet configuration as in the previous case, we attached two coils on the frame at a relative distance of 40 mm (or multiple of it) to obtain the phase matching of the output AC waveform. In this way, it is possible to (almost) double the signal output amplitude by connecting the two in series.

Bottle Dynamo - this is the standard supply system used to power position lights in city bikes. It provides an AC output that can reach peaks of a few Watts for high rotation speed. In our study, it has been used as a reference to compare the other approaches.

An efficient harvester requires a dedicated energy conditioning system to shape and store it for further load supply. Figure 4 depicts a block diagram of the designed energy harvesting solution for the presented IoT system.

A super capacitor is used as energy buffer to store the energy. Figure 5 presents a load sharing mechanism between the

Fig. 3: IoT device prototype: top and bottom sides

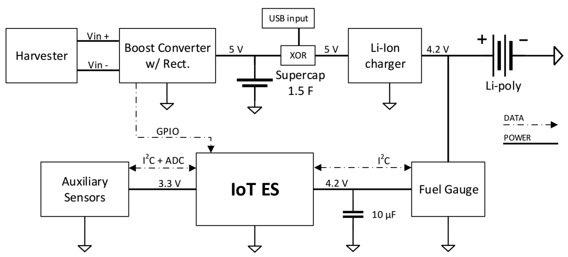

Fig. 4: Block diagram of the energy harvesting circuit.

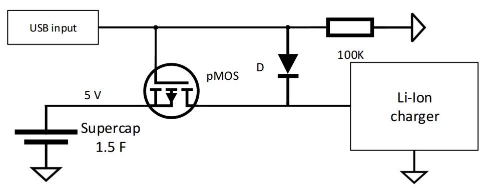

Fig. 5: Load sharing mechanism between two energy inputs for battery recharge.

harvester and conventional USB charging inputs. The energy harvester consists of two subsystems: the energy transducer itself and an energy conditioning and management circuitry. We evaluated two recent off-the-shelf integrated circuits (ICs) specifically designed for power conditioning and management in harvesting applications:

BQ25570 - manufactured by Texas Instruments, this IC is specifically designed to harvest μW to mW of power from high impedance direct current (DC) sources. As a main feature, this IC integrates a Maximum Power Point Tracking (MPPT) algorithm that allows it to maximize the energy extraction process with an efficiency up to 93%. It adaptively tunes its working point (by forcing a Voltage at the output of the energy converter) to a fraction of the open circuit Voltage (V_{OC}), periodically measured at the output of the converter. As drawbacks, (i) the MPPT feature starts when the Voltage of the storage connected to the BQ (super-capacitor or secondary battery) is higher than $\approx$1.75 V, which results in a very inefficient start-up phase (20$\div$30% efficiency); (ii) it requires an external rectifying circuit to exploit AC sources as the bottle dynamo or the custom inductive harvesters, severely impacting its efficiency.

LTC3588-1 - this IC, manufactured by Linear Technology, is specifically designed to be used with high impedance AC energy converters, like piezoelectric harvesters. As a main feature, it integrates a very efficient full bridge rectifying circuit and has a wide input Voltage range (up to 20 V). As a drawback, it does not feature the MPPT circuit.

We conducted several tests to characterize the performance of the six evaluated configurations. Figure 6 presents the output performance of four, out of the six configurations presented, with linear interpolation of the measured working points. The characteristic curves depicted represent the bottle dynamo interfaced with BQ and LTC ICs, the single inductive coil and the double coil both interfaced with the LTC IC. Minimum and maximum power registered by means of a small photovoltaic panel (5x11 cm, 17% efficiency) in outdoor

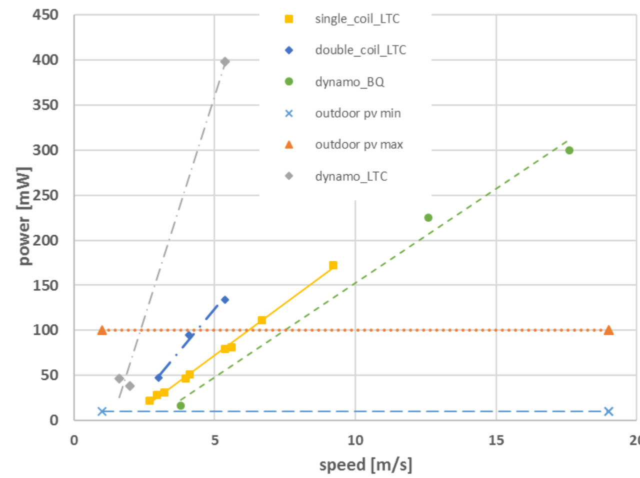

Fig. 6: Harvesting solutions power performance vs. speed

scenario is included as an alternative solution. The remaining two configurations are not reported because of the very low efficiency of the BQ IC that resulted in maximum extracted power in the order of few tens of μW, more than three orders of magnitude lower than the performance obtained with the LTC. The obtained results revealed a considerable difference in performance between the two studied boost converters. The bottle dynamo connected to the LTC chip outputs 400 mW, while it provides only 50 mW when interfaced with BQ. The LTC conditioning system outperforms BQ in all studied cases. Custom inductive systems demonstrate higher performance than expected, the single coil with an output power in the range of $\approx$20$\div$30 mW, riding the bike at 2.6 m/s (9.5 km/h), that exceeds the minimum output power level requirement for the designed harvesting subsystem. Moreover, the careful design of the series connection for the double coil is clearly visible in the characteristic, exhibiting almost double the output power with respect to the single coil. Figure 7 presents the IoT system battery discharge curves for various harvesting solutions at a fixed tracking scheduling (one GNSS localization sample and cellular data transmission per minute) and constant traveling speed (10 km/h). The data is obtained by simulating the system using the PASES environment [26] which includes battery modeling. In a real life scenario, with varying speed and varying energy harvesting performance, the system lifetime will be different. However, in the most common use case the estimated autonomy exceeds 1000 hours of continuous operation.

IV. Adaptive Tracking

Considering the amount of current drained by the tracking task, the first optimization step must be addressed at the software implementation level, to reduce waste of energy and delays the most. These choices must not trade-off the accuracy and reliability of tracking. On top of the lowest level procedures (like the interaction between Bluetooth, GNSS and GSM modems), the application can be designed according to the different use-cases and services to be provided. Basically, the development focuses on the selection of a static or adaptive scheduler that meets service requirements in terms of localization accuracy and tracking reliability.

In the connected bike scenario, we propose two tracking

Algorithm 1: Time based tracking algorithm

```
Input: currentTime, lastSamplingInstant, targetTime
while Forever do
    updateCurrentTime();
    elapsedTime = currentTime - lastSamplingInstant;
    if elapsedTime == targetTime then
        lastSamplingInstant = currentTime;
        samplePositionWithGNSS();
        storePositionInLocationsBuffer();
    end
    if getLocationsBufferState() == FULL then
        sendLocationsBufferWithGPRS();
        clearLocationsBuffer();
    end
    waitInLowPowerState(seconds);
end
```

Algorithm 2: Distance based tracking algorithm

```
Input: speed, lastSamplingD, targetD
while Forever do
    updateDistanceTraveled(speed);
    distanceTraveled = currentDistance -
     lastSamplingD;
    if distanceTraveled == targetD then
        lastSamplingD = currentDistance;
        samplePositionWithGNSS();
        storePositionInLocationsBuffer();
    end
    if getLocationsBufferState() == FULL then
        sendLocationsBufferWithGPRS();
        clearLocationsBuffer();
    end
    waitInLowPowerState(seconds);
end
```

approaches that ensure minimum execution time and power consumption, by minimizing the complexity and number of implemented instructions. The two approaches differ in the way the instant of GNSS interrogation and its duty-cycle are selected, namely the interval between sucessive tasks execution. The first is the widely adopted time-based (TB) approach, generalized by the pseudo-code presented as Algorithm 1. The second one is a distance-based (DiB) tracking approach, presented as Algorithm 2.

The TB tracking application is the simplest solution that can be implemented and yet the most reliable, since it is natively supported and integrated at the hardware level in modern GNSS modems. It is very convenient, particularly when a very high time resolution is required, in the order of coordinates refresh rate less than 10 s (for instance in car navigation systems). Thanks to the native support of such function, all the other components external to the GNSS modem can be kept in ultra low-power states instead of busy waiting. The DiB tracking application, instead, is based on the computation of the distance traveled by the bike to decide whether or not to activate the GNSS and refresh the location. This approach is not directly implemented in GNSS modems since it is more convenient, from the energy consumption point of view, to rely on external speed sensors and timers interfaced

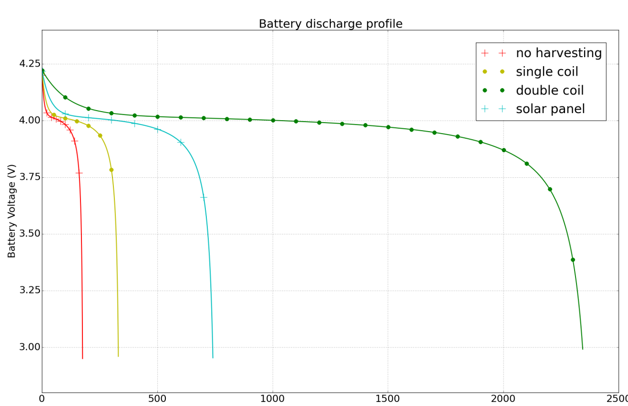

Fig. 7: Battery discharge profiles for various harvesting solutions

with a microcontroller to track the speed and evaluate distance traveled. The point of having two different tracking approaches is to let the user choose the most suitable one according to his/her own preference and needs.

The adaptive tracking approach represents a new degree of freedom for a connected bike. Moreover, it opens different higher level options of adaptability that can be transparent to the user. For instance, by post processing the user's historical data in the cloud, it would be possible to suggest the optimal tracking approach for each of the tour that he or she usually performs. Optimization is targeted to the minimization of the energy consumption still fulfilling the user preferences.

In both implementations of the tracking scheduler, the main contribution to the power consumption is reletaed to the communication sub-task. Thus, a basic power-aware optimization that we implemented in both cases is the capability of buffering data and delaying the transmission. In general, such solution represents an advantage only if a trade-off between buffer size, payload size (of the packets to transmit), communication protocol overhead per transmission and, finally, power consumption is found. We conducted several field tests, using the prototype hardware, to evaluate the power budget associated with different configurations. The results, depicted in Figure 8, show the system current consumption (on a 3.7 V LiIon battery) measured with the on-board fuel gauge, against buffer length and GNSS sampling interval. As a first observation, it is clear how the buffer size and the payload length do not represents an issue thanks to the adopted hardware and the reduced amount of bytes required by the GNSS data packet. By increasing the buffer size and reducing the number of transmissions in time, the average current consumption rapidly decreases below 20 mA, in the cases where the GNSS is read out with intervals larger than 20 s. In the very interesting cases where the buffer has a capacity of 10 GPS locations, the average consumption decreases well below 10 mA resulting in an average power consumption lower than 40 mW. These numbers demonstrate that the system can reach an energy neutral budget when the inductive harvesting system is used in conjunction with any of the two buffered tracking algorithms, with reasonably low travelling speed (as low as 3 m/s in the case of double coil harvester).

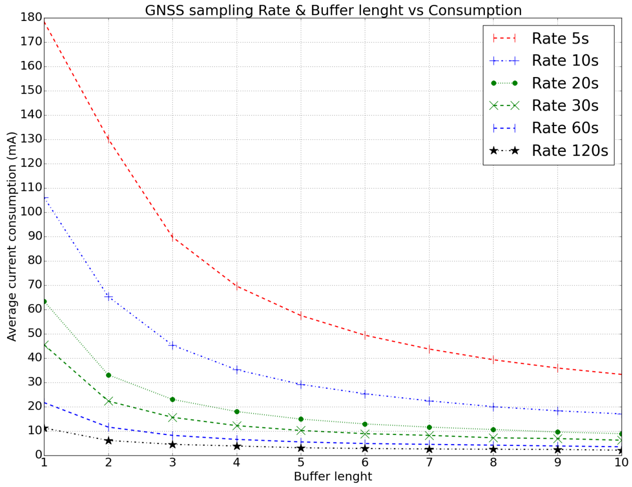

Fig. 8: Current consumption at various scheduling settings

V. Conclusion

In this paper we present a multifunctional IoT system designed for vehicles long-term tracking applications. The system integrates Cellular, GNSS and BLE communication technologies. The details of the system hardware architecture and functional modules are presented. The paper investigates various energy harvesting solutions and design of the energy conditioning subsystem, both at the hardware and the software levels) that meet application requirements. The presented design and solution demonstrate high efficiency and performance providing energy neutral features when the travelling speed is as low as 3 m/s and the on-line streaming of GNSS locations to the cloud server on the Internet is buffered.

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