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Residual Water Burst Detection Using WSN Measurements and Cloud Analysis*

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Abstract— **Water leakage and burst detection with increased accuracy represents an open issue in water management systems. Main challenges identified in this sector refer to lack of proper analysis tools and poor system state information. Stating from the water dynamics principles, we defined a model for water system characterization and pipe burst detection. We identified a minimum set of data needed for this information and proposed a WSN architecture for data acquisition. We computed the dynamic characteristics of a water supply shaft system and performed a cloud analysis of the system to determine the localization of the burst.**

I. Introduction

Network leakages represent a common and important problem in water distribution networks, leading to interruption of supply, water loses and material damages. Fast localization is of outmost importance. Two kinds of leakages are normally recognized, bursts and background leakages. First consists of larger leaks, that can be detected by visual inspection, and second consist of numerous small leaks throughout the network that are difficult or impossible to find.

The occurrence of a sudden leak in a pipeline causes a pressure decrease which is followed by a transient wave travelling upstream and downstream along the pipeline. As in any wave phenomenon, including the case of sonic waves, the reflection and refraction will adapt in case of changing the propagation conditions. A change in the conditions at the boundary, at some point of the pipeline, causes local flow changes pressure, changes that are transmitted from near to near, at a speed, called speed propagation, due to the elasticity of the fluid and the material of the pipe, forming waves flow and pressure respectively. Because of the hammer effect, the propagation speed is hard to be separated from the propagation speed in the liquid at rest. Under these considerations, proper localization of a pipe leak is a difficult task. Main drawbacks come from the lack of relevant network state information.

Considering their flexibility in covering large distributed areas, wireless sensor networks (WSN) are becoming increasingly popular in water management system applications. Typical WSN in industrial applications are powered directly from a supply or from batteries loaded by solar panels, removing the limitations regarding node power autonomy. They enable easy access to critical network state information, like water pressure and flow, using accessible communication networks. Depending on the characteristics of the monitored area, GPRS communications or a combination between GPRS and radio communication is used. Radio communication is used in point-to-point networks, especially when the number of nodes is high and there are limitations regarding the implementation cost. GPRS comes with greater reliability and more flexibility regarding possible implementation solutions, as the communication infrastructure is managed and guaranteed by a data service provider.

Researches and industrial professionals showed an increasing interest towards the development of Cloud-assisted SCADA (Supervisory Control and Data Acquisition) systems to reduce operational expenses and enable smart industrial systems [1]. This allows increased data accessibility, easy maintenance, high flexibility and scalability. Still, the approach of moving a SCADA application completely to the Cloud poses significant security problems, as it needs to integrate new and old communication technologies.

This paper proposes a water management system that uses a WSN over GPRS for sensors data acquisition and implements SCADA to Cloud integration to facilitate the implementation of a burst detection and localization algorithm. Section II focused on reviewing related work in for leakage and burst localization, their field of application and proposed architectures for WSN-SCADA-Cloud integration. Section III presents the implemented leak size detection algorithm. Section IV presents the equations behind the burst localization method. Section V exemplifies how the wave speed can be determined in iron water pipes. Section VI presents the characteristics of the water management application. Section VII shows the obtained results for the identification and localization of a simulated pipe burst. Section VIII concludes this paper.

II. Related Work

Key performance indicators for the assessment of water leakage techniques are the accuracy of the localization, the

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leak size estimation and the detection speed. Current research interest focuses on automatic and fast detection of leaks using easily deployable wireless sensor networks or Cyber Physical Systems for data acquisition [1], [3].

Methods for signal processing in leakage detection techniques are mostly focused on a time or frequency analysis of the pressure parameter [4]. A classification of such techniques according to their domain is presented in [1]. Their field of application differs from methods that can be applied on a single pipeline, like Leak Reflection Method (LRM), Transient Damping Method (TDM) or Inverse Transient Method (ITM), to methods adapted for pipelines with multiple branches like Wavelet Packet Analysis (WPA) [3].

A review of efficiency between different leak detection methodologies that use pressure transients was presented in [5][6]. This analysis showed that LRM and TDM obtained best performance regarding the small dimension of the leak (0.01 – 0.04l/s) and shortest inspection range.

LRM is a method suitable for single pipe analysis. It analyses the wave propagation inside a pipeline, creating observable variations [7]. The difficulty of this approach is the need of accurate pressure measurements. Measurements in such systems can be affected by irregularities in pipe interconnections or a high rates of deposits.

TDM is a simple method that compares a signal with a benchmark damping pattern, obtained in a leak-free system. The method can be used only in single-pipe linear systems, with steady friction [8].

Mpesha et al. [9] revealed presence of leak or anomalies by amplitude peaks in frequency response diagram of pressure signals. These peaks have comparatively lower amplitude than leak free system. The change in amplitude of peaks shows pressure drop due to presence of leak [10]. Lee et al. [11] introduced inverse resonant and peak sequencing method (PSM) which is based on the fact that leak produces sinusoid patterns on peaks of FRDs (frequency response diagram). Although friction also causes attenuation, it has a smooth distinguishable pattern in leak induced signals which does not affect this approach much [11].

The use of WSN for monitoring distributed water systems allows accessible data collection over long distances. Depending on the available resources, processing can be distributed over several nodes, like in [1], or can be centralized at a SCADA (Supervisory Control and Data Acquisition) center. While distributed control provides many advantages like lower data rates and node density, a centralized approach can be applied more easily on existing systems and allows the use of model-based methods identify leakages by comparing measured data with predicted values [12]. Both centralized and distributed architectures can benefit from the integration in a Cloud system by allowing easy data sharing, real-time analysis and data storage reliability. Several WSN solutions available on the market provide integrated public Cloud connectors for data storage [13]. Cloud services for complex functions implementation and execution allow fast execution of process model and rapid leakage detection, even in large distributed systems.

III. Burst Size Detection

In a water pipe system the main feature of the flow and pressure waves is that they are associated, meaning they are formed and propagated simultaneously. The relationship between these associated waves was proposed by Vasili Joukowski [14].

The water hammer effect theory uses the fundamental Joukowsky equation to model the wave propagation inside a pipe, in case of a leak. We can relate pressure changes to velocity changes by using:

$$\Delta p = \rho \cdot c \cdot \Delta v \tag{1}$$

where ρ is the fluid mass density and c is the speed of sound.

The pressure rise formula can be applied only when the change in velocity is faster than the time it takes for the burst-induced wave to reach the induction point after reflection from the boundary. When closing a valve at the downstream end of a pipeline, a change in velocity ΔV must occur in less than $2 \cdot L / a$ seconds, where L is the length of the pipeline and a is celerity, the velocity of wave propagation.

If we substitute the velocity with $V = Q \cdot A$, the Joukowsky pressure variation into a horizontal pipe becomes:

$$\Delta H = -\frac{a}{g} \cdot \Delta V = -\frac{a}{gA} \cdot \Delta Q \,, \tag{2}$$

where ΔH is the piezometric quota, ΔQ is the flow, and A is the pipe section.

In the case of a burst event somewhere along the pipe, the sudden change in flow (velocity) is caused by a side discharge through the burst orifice and is equal to the burst flow $\Delta V = Q \cdot B$, where B is characteristic impedance of the pipe. The impedance of pipe sections immediately upstream and downstream of the burst is equal. Therefore, the upstream and downstream flows after the burst occurs are:

$$Qu = Qo + \frac{1}{2} Q_B \tag{3}$$

$$Qd = Qo - \frac{1}{2} Q_B \tag{4}$$

where Q_0 is the initial flow, Q_u is the upstream flow after the leak occurs, and Q_B is the flow through the leak.

The Joukowsky formula was derived for a pressure wave propagating upstream. Applying (2) at any point upstream from the burst we obtain the upstream rise:

$$\Delta H_{Bu} = -\frac{a}{g \cdot A}\left[Q_o - \left(Q_o + \frac{1}{2} Q_B\right)\right] = -\frac{a \cdot Q_B}{2 \cdot g \cdot A} \tag{5}$$

where g is gravitational acceleration.

The same analysis can be applied for the wave propagating downstream. In this case, the Joukowsky formula becomes:

$$\Delta H = \frac{a}{g \cdot A} \cdot \Delta Q \tag{6}$$

Applying (6) at any point downstream from the burst we have the following equation for the downstream rise:

$$\Delta H_{Bd} = \frac{a}{g \cdot A}\left[Q_o - \left(Q_o + \frac{1}{2} Q_B\right)\right] = -\frac{a \cdot Q_B}{2 \cdot g \cdot A} \tag{7}$$

From (5) and (7) we can see that $\Delta H_{Bu} = \Delta H_{Bd}$. This means that negative pressure waves of equal magnitude ΔH_B travel in opposite directions away from the burst point:

$$\Delta H_B = -\frac{a}{2 \cdot g \cdot A} \cdot Q_B \tag{8}$$

where ΔH_B is the magnitude of the burst-induced pressure wave (from the pressure measurement).

The burst flow can be calculated using the orifice equation:

$$Q_B = C_d \cdot A_o \cdot \sqrt{2 \cdot g \cdot H_B} \tag{9}$$

where $C_d \cdot A_o$ is a lumped discharge parameter describing the size of the burst, and H_B is the head at the burst point. Solving (8) for burst flow Q_B gives:

$$Q_B = -\frac{2 \cdot g \cdot A}{a} \Delta H_B \tag{10}$$

By substituting (10) into (9), the expression for the burst size is derived:

$$C_d \cdot A_o = -\frac{A \cdot \Delta H_B \cdot \sqrt{2 \cdot g}}{a \cdot \sqrt{H_B}} \tag{11}$$

Considering that a burst orifice discharge Q_B will always be positive and pressure change ΔH_B will always be negative, (11) can be rewritten as:

$$C_d \cdot A_o = -\frac{A \cdot \sqrt{2 \cdot g}}{a \cdot \sqrt{H_B}} \tag{12}$$

The head at the burst point H_B can be found by subtracting ΔH_B from the initial head value H_0:

$$H_B = Ho - \Delta H_B \tag{13}$$

This equation does not provide the exact size of the burst due to the neglect of frictional effects. However, it still provides a reasonable estimate, which can be used to evaluate the severity of the burst.

IV. BURST LOCALIZATION METHOD

We take into account pressure measurement in one and two points along the pipe. In the one point method the measurement (P1) takes place near first shaft and it is used to the measure the direct and reflected wave caused by the leak considering the hammer effect (Fig. 1). In the case of two point measurement, the direct hammer effect wave can be observed in the pressure variation in the respective points. Both methods show the propagation wave speed considering an iron water pipe.

A. One Point Measurement

By using a simple prediction model for the pressure parameter and comparing the predicted value with measured one, we can detect a direct wave perturbation after a t_1 time from the moment of leak:

$$L - x = V \cdot t_1 \tag{14}$$

where L is the length of the horizontal pipe, x is the distance from the pressure point S10 where the burst is located, and V is the speed of sound in liquid.

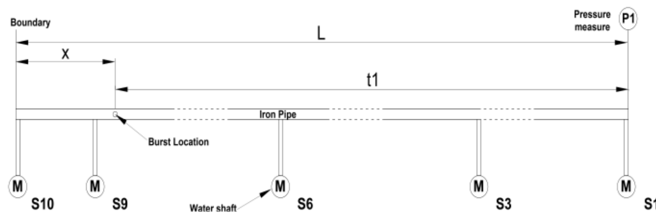

Figure 1. One point pressure measurement.

The reflected wave is detected after a t_2 time from the moment of burst (15):

$$L + x = V \cdot t_2 \tag{15}$$

So, the burst location is established by (16).

$$x = \frac{V \cdot (t_2 - t_1)}{2} \tag{16}$$

B. Two points measurement

In this case, illustrated in Fig. 2, we take into consideration how a leak is identified, using the one point method, at the first measurement before (by sensor S10) and after (by sensor S1) the localization point on the water flow. The perturbation induced by the direct wave is detected by the sensor S10 at the moment t_1 and at t_2 by the second sensor, from the moment of the burst:

$$x = V \cdot t_1 \tag{17}$$

$$L - x = V \cdot t_2 \tag{18}$$

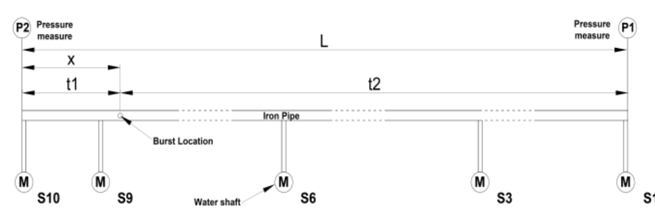

Figure 2. Two points pressure measurement.

In this case burst location can be found with:

$$x = \frac{1}{2}\left[L - V(t_2 - t_1)\right] . \tag{19}$$

V. DETERMINING THE WAVE SPEED

Because of the hammer effect, a leak initiates a wave propagated in both directions along the pipe. The speed of this wave depends on the characteristics of the liquid and on the pipe material. The wave has constant speed, but due to the amplitude amortization, after a while the wave is switching off.

The value of speed waves is essential for correct evaluation of the wave effect; therefore, it is necessary to know its real value or to appreciate a value as much closer to the real one.

Equation (20) gives the formula for computing the wave speed taking into account the elasticity of the fluid and the characteristics of the pipe material.

$$V = \frac{\sqrt{\frac{\varepsilon}{\rho}}}{\sqrt{1 + C_1 \frac{\varepsilon}{E}\frac{D}{e}}} \tag{20}$$

The significance of the notation in (20) are presented in Table

TABLE I. SIGNIFICANCE OF NOTATION IN (20)

Nota-tion	*Significance*	*value*
ε	fluid elastic modulus	For water : $2.1{\cdot}10^4$ kgf / cm^2 = $2.1{\cdot}9.81{\cdot}10^8$ Pa
ρ	density of the liquid	For water: 1 000 kg / m^3 = 101.9 $kgfs^2$ / m^4
E	modulus of elasticity of the pipe material	For iron: $2.1{\cdot}10^6$ kgf / cm^2 = $2.1{\cdot}9.81{\cdot}10^{10}$ Pa
D	inside diameter of the pipe	200 mm (our case)
e	thickness of the pipe wall	10 mm (our case)
C_1	coefficient [a]	0.796 (see the condition below)

a. C_1 is a coefficient which takes into account the wall thickness of the pipe and the conditions of its support as follows.

For pipe walls the ratio D/e <25 and, if the longitudinal displacements are prevented, we have the coefficient value:

$$C_1 = \frac{2e}{D}(1+\mu) + \frac{D(1-\mu)}{D+e} \tag{21}$$

where μ is the Poisson coefficient (For iron μ = 0.27- 0.3).

If we use the values according to our application characteristics, as explained for (30), we have D/e=20. We will use μ = 0.3 for the iron pipe, leading to a value for the C_1 coefficient of 0.796. We obtain the value of wave speed:

$$V = 1333\text{m/s} \tag{22}$$

VI. WATER SYSTEM DESCRIPTION

The methods presented in previous sections for burst detection are implemented in a residual water shaft system (Fig. 3). Ten wells are placed in line and connected to a collector pipe having the length L_1 = 2100 m. The pipe continues with a slope of a length L_2 = 475 m and height H = 35m to reach the water tanks, located on a near hill.

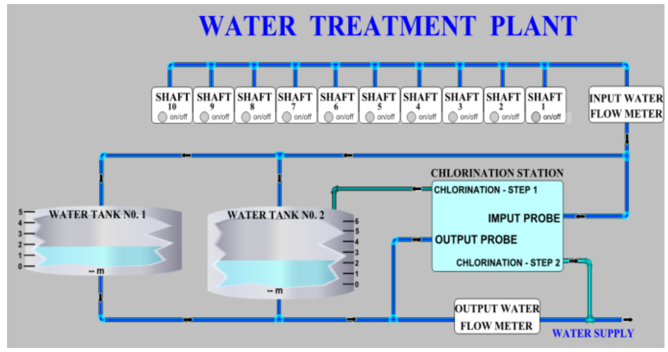

Figure 3. Water treatment plant architecture.

Each water shaft is equipped with a sink pump and level, pressure and flow measurement devices. These parameters can be monitored on local HMI (Fig. 4). A local PLC implements control rules and transmits pump parameters, shaft water level, pressure in the water pipe, and the water volume pumping in the main pipe, to the SCADA Control Center (Fig. 5), located near water tanks. Data transmission is done through GPRS. In order to maintain a constant level and to ensure, as much as possible, equal working hours of the shaft pumps the SCADA system controls the filling of the water tanks.

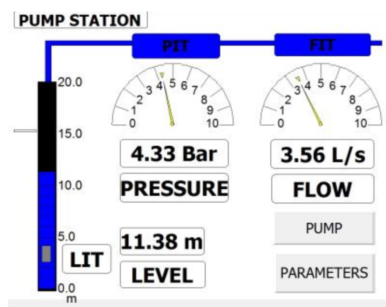

Figure 4. HMI water shaft parameters.

The SCADA software is from TAC VISTA and allows the implementation of customized functions for the centralized analysis of the burst localization. A VIDEC server is used to receive data via GPRS from the field shaft using the UDP protocol. Each local shaft has a WAGO PLC with a GPRS modem and a dynamic IP given by the service provider. Use of the VIDEC software for the communication allows the use of an external static IP only at the SCADA level. Communication is bidirectional and uses the standard OPC automation protocol.

After treatment, water tanks supply approximately 10,000 consumers using gravitational laws for the distribution. Due to the strategic importance of this system, operators need continuous monitoring and fast detection of pipe burst. Experience showed that without a proper system monitoring and using old on-the-field methods for burst identification can take days for burst localization. For that we consider a method, to determine as much as possible the burst location.

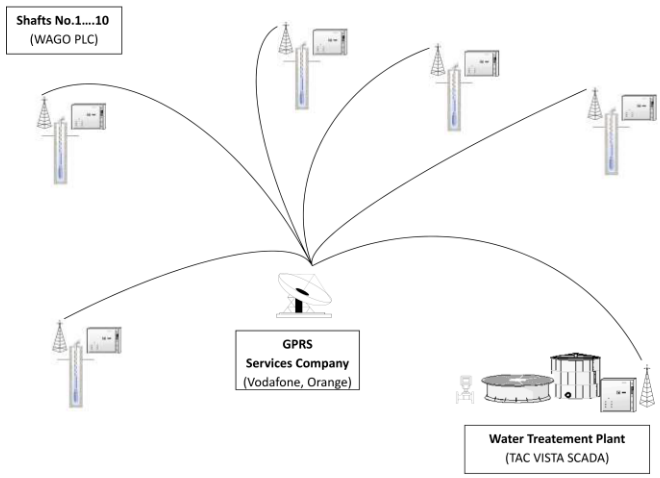

Figure 5. WSN communication architecture.

Cloud integration allows securing process data and enables process modelling and performance analysis on large periods of time. Using Microsoft Azure SQL database features allows the development of a cloud database and can be integrated with the "Functions" module for the implementation of the burst detection algorithm. The interconnection between SCADA and cloud modules is illustrated in Fig. 6. Direct logging of WSN data into the cloud leads to high bandwidth and significant higher costs than through a SCADA server. For this reason the cloud platform is chosen only for historical data storage and data analysis. Data acquisition from SCADA is done using a DBMS connection, each 10 minutes. We defined two tables, one for pressure and one for flow, having as lines the acquisition timestamp and as columns the different monitoring points. We implemented a dashboard to display the variation graph of pressure values between each two consecutive points. We defined an event triggered function for burst localization. It can be executed by associating its corresponding service on a dashboard button. The results is transferred through HTTPS to the client application.

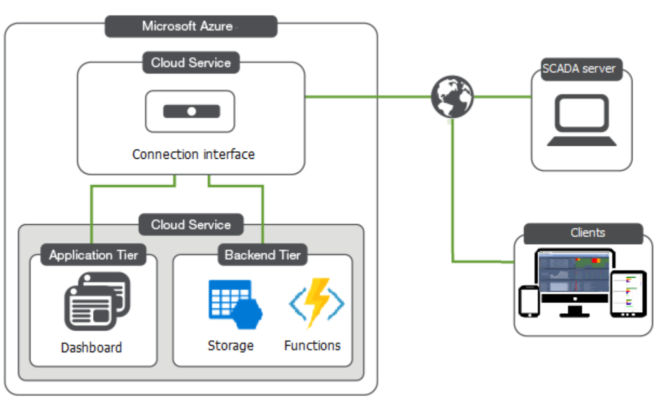

Figure 6. Interconnection with cloud modules.

VII. Experimental Results

We used the methods described in sections III, IV and V to evaluate the performance in burst detection for the application presented in section VI. To this end, two pressure sensors were mounted at the beginning (P1) and, respectively, at the end (P2) of the horizontal collecting pipe L_1. To simulate a burst we opened a valve mounted on the collecting pipe. We recorded the pressure values at 250 ms. For evaluation we chose the two point pressure measurement, instead a measurement with a single point, because in the latter case the reflected wave is difficult to determine due to interferences and relative big time between iterations.

We simulated a burst in point x at a distance of 588 m from the point P2 and recorded the pressure values. Because samples are recorded at each 250 ms, the exact time of the leakage is determined with a corresponding error. According to (19), burst location can be determined using the time difference between previous recorded samples.

If $\theta = t_2 - t_1$ is positive (the wave is first detected by sensor P1, as in Fig. 7) it means the burst is located between P1 and the middle of the pipe. If θ is negative (as presented in Fig. 8), we can conclude that the burst is between the middle of the pipe and P2. When θ is approximately 0, the burst is located close to the middle of the pipe (Fig. 9).

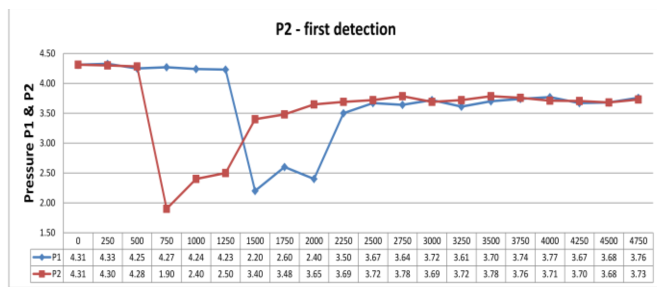

Figure 7. Pressure representation in case of a burst in the first half of the pipe.

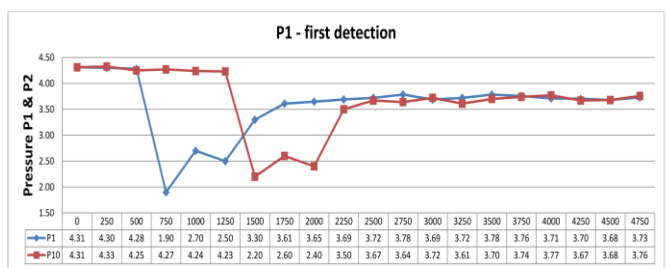

Figure 8. Pressure representation in case of a burst in the first half of the pipe.

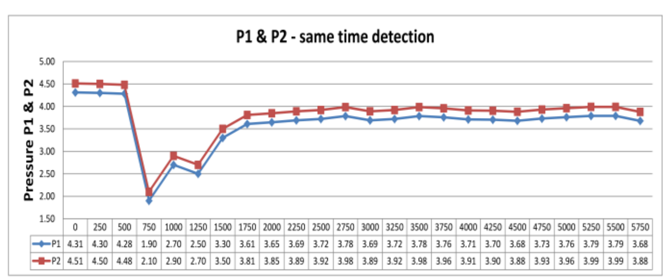

Figure 9. Pressure representation in case of a burst close to the middle of the pipe.

Because the measurement takes place at each 250ms, the exact location of the burst is approximated linearly between recorded pressure values. According to (19) the location of the burst depending on the time interval between its identification in the two measuring points is illustrated in Table 2.

TABLE 2. BURST LOCALIZATION

t_1(ms)	0	250	500	750	1000	1250	1500
t_2(ms)	1500	1250	1000	750	500	250	0
θ (ms)	1500	1000	500	0	-500	-1000	-1500
x (m)	50.25	383.5	716.75	1050	1383.25	1716.5	2049.75

Considering the computed wave velocity c = 1333 m/s and the time of t = 250 ms between measurements, the distance crossed by the wave is 333.35 m. This means that maximum error caused by the pressure reading timestamp is equal with 166.62 m. Then the relative error is in the interval [-8.5 %, +8.5 %].

VIII. CONCLUSIONS

This paper presented and evaluated two algorithms of burst size detection and burst localization in a water management application. We implemented a GPRS-based WSN for the monitoring of a multipoint water pumping station. This allowed easy deployment of local nodes and access to more data for the evaluation of the process state. Data was gathered in a SCADA server connected to a Cloud application. We simulated a burst between two points and evaluated how this information is reachable to the correct level of the business process. The cloud platform analysis also helped in the fast and accurate localization of the burst. The application represents a proof of concept on how current technologies, with increasing accessibility, can be used to improve operation practices in SCADA systems. Choosing a public cloud ensures improved security and facilitates a process engineer access to appropriate services for the deployment of analytics functions. Future work will include implementation of a real-time fault identification algorithm and its performance evaluation using the current setup.

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