Wireless Critical Process Control in oil and gas refinery plants

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***Abstract*— Wireless telemetry systems are now becoming a relevant topic in the field of critical process control in industrial plants and oil/gas refineries. In contrast to wireline communication, wireless links are inherently unreliable. This unreliability depends critically on the propagation environment of the radio-links as the layout of scattering objects (pipes and metallic structures) influences the strength and the fluctuations of the received signal power. The development of next generation critical process control systems using the wireless technology calls for the design of advanced network architectures. By following the guidelines introduced by recent standardization, this paper proposes a novel architecture based on the most recent technological advances to enable wireless advanced process control for tight closed loop applications. Cooperative network paradigm is indicated as the key technology to provide link reliability even in critical environments. A cooperative link-layer protocol has been developed and tested over a IEEE 802.15.4 compliant radio network deployed in non line-of-sight (NLOS) propagation environment with dense metallic obstacles. Test-bed measurements evaluate experimentally the benefits of the cooperative architecture.**

I. Introduction

The increasing demand of oil and gas supplies frequently requires the design and execution of very large production and processing plants over remote locations with harsh environmental conditions and challenging logistics. The adoption of cabling to fully interconnect machines and monitor/control large number of processes is becoming unfeasible due to the high fluctuations of installed industrial wiring costs [1]. The opportunity to replace cabling by deploying a wireless sensor network (WSN) is now becoming of strategic interest for most oil contractor projects. The installation of wireless sensors may give significant cost savings for a variety of typical plants such as revamping/expansions of existing facilities, storage tanks, utilities like water treatment, interconnecting lines, manifolds, high stacks, etc... In addition, the full plant coverage with WiFi and WSN opens the door to many new applications which are going to be requested by the end users in the near future. Therefore, developing consistent design methodologies for the deployment of a wireless sensor network system is becoming mandatory for most oil contractors to monitor the technology suppliers/vendors during every phase of the wireless system set-up and testing.

An example of a 3D view of an oil refinery is illustrated in Fig. 1: typical locations of wireless devices used for remote control and monitoring of industrial petrochemical plant sites are characterized by harsh (and hazardous) environments where propagation is subject to scattering from dense metallic objects (tubes, structural pipe racks, metallic towers and building, etc...). Current wireless architectures for industrial control and monitoring are based on the IEEE 802.15.4 standard [2] and prevent the adoption of wireless in emergency actions and tight process control loops [3]. Wireless networking is typically considered for less time-critical monitoring tasks as supervised control (with human in the loop), leakage or machine health monitoring [1].

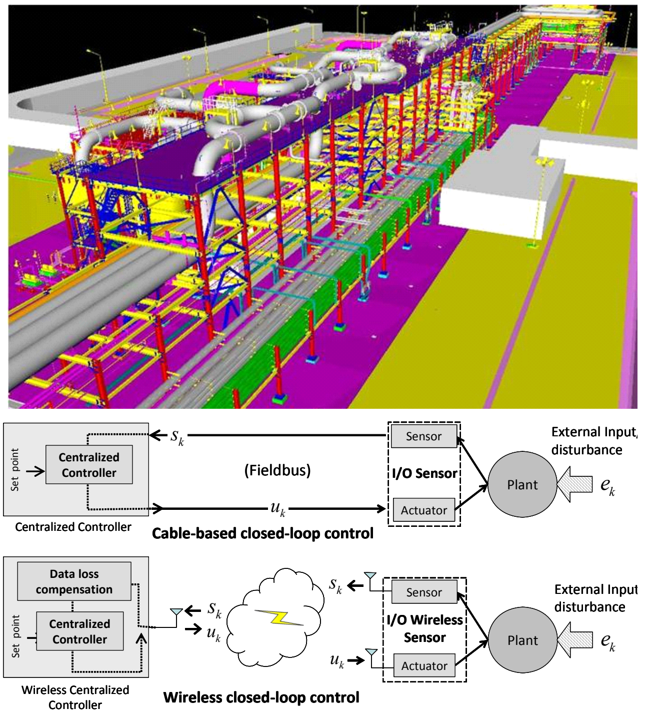

Fig. 1. Top figure: 3D CAD view of oil refinery. Bottom figure: cable-based vs wireless closed-loop control systems.

A. Wireless technology for the Oil&Gas industry

In what follows we outline the most relevant cable replacing applications of strategic interest for the Oil&Gas industry.

APC (Advanced Process Control). The process industry is strongly pursuing improvements in the performance of the plants. The WSN technology allows an easy and cost effective possibility to install additional monitoring points in the plant in order to allow the use of the most innovative APC systems.

Predictive maintenance and diagnostic. Another key factor to improve the performance and the availability of the plant and at the same time reduce its maintenance costs is to optimize the maintenance activities. This can be achieved by the predictive maintenance systems. Also these kind of systems require additional monitoring points which may require to be moved around the plant based on the maintenance plans (e.g. thermo-cameras). The WSN technology allows an easy and cost effective possibility to install additional monitoring points in the plant in order to allow the use of the most innovative computerized maintenance management systems (CMMS).

AMS (Asset Management System). The following points are of utmost importance for the optimal management of the field instrumentation: *i)* remote access to all the parameters of the installed devices; *ii)* remote calibration and test (e.g. partial stroke test); *iii)* automatic recording of all the test results as well as storage of all the configuration data. Wireless devices can make all these functionalities available in control room, similarly to what plant operators are used to get with wired smart devices.

End-user operators and maintenance personnel can benefit of many other applications that can be integrated with the wireless infrastructure, to name a few: *i)* radio-frequency identification (RFID) and personnel location in the plant; *ii)* portable wireless gas detectors; *iii)* RFID for equipment tags to implement an advanced maintenance scheduler system; *iv)* portable human machine interface (HMI), ATEX compliant WiFi stations; *v)* portable measurement devices; *vi)* portable cameras or thermocameras.

In addition to refining applications, wireless technology has been also recently proposed to replace cabling in land exploration applications [4].

B. Wireless control loops in Oil&Gas refinery

Focus of this paper is on critical wireless control loops systems. Networked control loop systems require the controller and the plant to be connected via a two-way digital communication channel of limited bandwidth. As depicted in Fig. 1 (at bottom) sensors are monitoring the state of a process and periodically forward the digital measurements (s_k) to a remote controller. Based on these measurements, the remote controller computes a control message (u_k) according to a given policy and sends it to the actuator over the feedback channel. Upon retrieval of controller message, the actuator applies an appropriate control signal to adjust the plant state. For process control applications, determinism and reliability of data transfer is a key issue, and cycle time (round-trip time) is a critical parameter to guarantee process stability [5]. Reliable communication occurs *only* if both measurement s_k and feedback control u_k are decoded by respective parties within specified deadlines defined by the control policy. This *hard* real-time constraint calls for the development of advanced protocols for wireless link-layer management and a complete revision of conventional network architectures for just monitoring.

Error-control methods enhance the reliability of wireless communications by basically adding link-by-link redundancy to data packets. When a packet is lost, an automatic explicit repeat request policy is implemented. The adoption of explicit acknowledgements for error control adds additional delays causing instability of the plant states and it is not acceptable for tight process control applications. Current proposals for multi-hop auto re-route architectures are therefore not the best option for cable-replacing in tight closed loop.

Contribution of the paper. This paper focuses on the most promising technologies to support next generation wireless advanced critical process control systems. It is envisaged here that the incorporation of the cooperative network paradigm [6] into future system standardization will allow cable-replacing in tight closed-loop control applications with cycle-time below 100ms [3]. Cooperative communication systems allow devices to emulate transmission and reception of data on a virtual antenna array [7]. A proprietary cooperative link-layer protocol tailored for closed-loop process control applications has been developed on top of an existing IEEE 802.15.4 compliant PHY/MAC layer design. Real-time control has been tested in an harsh environment with non line-of-sight (NLOS) propagation and dense obstacles. Preliminary results from test-bed measurements confirm that cooperative communication is a promising paradigm to enable next generation critical wireless control systems as it provides clear performance advantages compared to classical network architectures in terms of link reliability and closed-loop stability performance.

II. Wireless process control networks

In what follows we consider a control network where both sensing and feedback control are clock-driven. Output sensor in active state is periodically sampling a continuous signal $\mathbf{s}(t) \in \mathbb{R}^m$ with period T_s (reporting rate) to obtain the time vector series $\mathbf{s}_k = \mathbf{s}(t_k)$, $t_k = kT_s$. Discrete signals $\mathbf{s}_k \in \mathbb{R}^m$ provide an observation of the plant state vector $\mathbf{x}_k \in \mathbb{R}^q$. Plant model for process observations is described in discrete-time state-space form

$$\begin{aligned} \mathbf{s}_k &= \mathbf{C} \times \mathbf{x}_k + \mathbf{n}_k \\ \mathbf{x}_k &= \mathbf{A} \times \mathbf{x}_{k-1} + \mathbf{B} \times \mathbf{u}_k + \mathbf{D} \times \mathbf{e}_k + \mathbf{w}_k \end{aligned} \tag{1}$$

At time t_k the plant vector state $\mathbf{x}_k$ is a function of the previous states $\mathbf{x}_{k-1}$, the feedback control variable $\mathbf{u}_k \in \mathbb{R}^v$ and an external random input process $\mathbf{e}_k \in \mathbb{R}^v$ acting as external non-stationary disturbance. Feedback control $\mathbf{u}_k = \mathbf{G}(\mathbf{x}_{k-1}|\tilde{\mathbf{x}}_k)$ follows a generic control law function $\mathbf{G}(\cdot)$ that depends on the previous vector state $\mathbf{x}_{k-1}$. Purpose of the controller is to stabilize the system by balancing the external input disturbance and minimizing the deviation of plant states $\mathbf{x}_k$ from the desired stable set-points indicated here by $\tilde{\mathbf{x}}_k$. Round-trip latency T_{RT} is a critical parameter for process control and it is defined as the time between sampling and transmission of observation s_k, and the successful decoding of feedback control message $\mathbf{u}_{k+1}$ by remote actuator. We assume that observation $\mathbf{s}_k$ provides a full state measurement of $\mathbf{x}_k$ and is affected by a scaling factor modeled as a full-rank matrix $\mathbf{C}$. Instrument AWG noise $\mathbf{n}_k \in \mathbb{R}^m$ with $\mathbf{n}_k \sim \mathcal{N}(\mathbf{0}, \sigma_n^2 \mathbf{I})$ includes quantization effects. Noise term $\mathbf{w}_{k+1} \in \mathbb{R}^q$ accounts for the state disturbance and is modeled as independent AGN noise with $\mathbf{w}_{k+1} \sim \mathcal{N}(\boldsymbol{\mu}_w, \sigma_w^2 \mathbf{I})$, so that $\mathbf{x}_0 = \boldsymbol{\mu}_w$. A networked control system that satisfies the stabilizable properties [5] needs two additional conditions to guarantee closed-loop stability: *i)* observation $\mathbf{s}_k$ and feedback control $\mathbf{u}_k$ are successfully decoded by the respective parties; *ii)* tolerable round-trip latency is $T_{\mathrm{RT}} < T_s$.

In this paper the main focus is on cable-replacing for tight closed-loop control system requiring $T_{\mathrm{RT}} < 100ms$. This is a reasonable choice to address most critical industrial process control applications [3]. The case for highly critical control (e.g., motion control) requiring cycle times of $T_{\mathrm{RT}} < 10ms$ is not considered here as still too challenging for implementation over current low-power wireless technology.

A. Wireless physical link modeling

In what follows the basics of wireless link performance modeling are reviewed. To simplify the reasoning, we assume the output sensor and the actuator be co-located and referred to as Input/Output sensor (I/O sensor). Extension to a more general model is straightforward. Both the controller and the I/O sensor are deployed at fixed locations over the plant and equipped with a radio device characterized by a single omnidirectional antenna transceiver and a limited battery energy supply mainly used for the transmission, reception and processing of data. Transmission of measurements $\mathbf{s}_k$ (over uplink) and feedback control $\mathbf{u}_k$ (over downlink) is subject to half-duplex constraint so that they occur in different time slots and satisfy the round trip delay constraint T_{RT}. Let $d_{I,C}$ be the distance between the I/O sensor I and the controller C, the probability of successful closed-loop control P_c is modeled by outage probability

$$P_c = \Pr[\min\{\gamma_{I,C}, \gamma_{C,I}\} \geq \beta] \tag{2}$$

where $\gamma_{I,C}$ the instantaneous Received Signal Strength (RSS) measured by the controller C over the uplink, while $\gamma_{C,I}$ is the RSS observed by the actuator I over downlink. Receiver sensitivity β with typical value of $\beta = -90dBm$ [8] depends critically on modulation of signals, hardware implementation, thermal and man-made background noise. Man-made noise in industrial environments can be originated by several sources like remote controls, motors and microwave furnaces [9].

In radio propagation the main scatterers/objects contributing to the received signal power attenuation are confined around the direct ray from transmitter-receiver pair: in wireless jargon this area is referred to as the Fresnel zone. Based on this assumption, the RSS for a wireless link (a, b) is modeled as $\gamma_{a,b} = g_{a,b} \times G_T G_R P_{\mathrm{T}}$ where G_T and G_R are the transmitter and receiver antenna gain, respectively. P_{T} is the transmit power while the attenuation due to radio propagation $g_{a,b} = h_{a,b} \times d_{a,b}^{-\alpha}$ is influenced by the nearest scattering objects. Attenuation consists of a deterministic distance dependent component $d_{a,b}^{-\alpha}$ with path-loss exponent α and of a random term $h_{a,b}$ that makes the RSS to fluctuate due to time-varying multipath fading.

Assuming as worst case statistical independence between uplink and downlink RSS fluctuations[1], successful control probability P_c can be rewritten as the the product of the success probabilities over uplink and downlink

$$P_c = \underbrace{\Pr[\gamma_{I,C} \geq \beta]}_{\text{Uplink: Sensor -> Controller}} \times \underbrace{\Pr[\gamma_{C,I} \geq \beta]}_{\text{Downlink: Controller -> Actuator}}. \tag{3}$$

The probability of successful control P_c is the indicator of networked control quality as stability is primarily ruled by packet losses that cause frequent interruptions of closed-loop control [10].

B. Virtual network planning and design for critical control

Commercial wireless systems adopt the multi-hop architecture as it allows data to be forwarded from a source to destination node throughout intermediate repeaters, along a route that can be dynamically changed according to network requirements (e.g., configuration, fault-tolerance, quality of radio link, battery state). The inherent unreliability of wireless links makes radio network planning a fundamental step that must be carried out prior to actual deployment of sensors. Virtual radio planning is based on the prediction of wireless link quality. Prediction can be supported by independent radio measurement campaigns over typical refinery environments [11] and/or by empirical propagation models. A low accuracy in the radio planning design phase will turn into a big issue during the commissioning phase. Adding new wireless repeaters to improve the coverage as well as moving them around the plant may require to re-open excavations along the cable route which is totally unacceptable during the commissioning (or even pre-commissioning) phase of the plant. For this reason it is crucial to develop design guidelines and tools that can allow to achieve a reasonable accuracy in the prediction of the wireless coverage. This approach will also limit the need to oversize the design of the overall system (which is obviously an extra cost for the contractor). After the mechanical completion, the on-site radio frequency survey is supposed to confirm the design with few small modification in order to limit the reworks to a percentage which is in line with a regular installation of a wired system. Making use of the 3D model during the design phase is of utmost importance to achieve this result.

III. Cooperative networks for process control

A cooperative network architecture allows machine-to-machine communications by involving a large number of intelligent devices sharing information and making collaborative decisions without direct human intervention. The architecture consists of separate radios encoding and transmitting their messages in coordination [6] over multiple redundant paths (spatial channels) to guarantee an highly reliable connection between source and destination. Cooperative communication offers the potential to be less sensible to isolated wireless link failures compared to multi-hop architecture as it creates a network of multiple paths where the same information is spread to maximize path redundancy and spatial diversity.

In what follows we propose the adoption of a cooperative network architecture to support next generation wireless

[1] This is also confirmed in practice by measurements over 2.4GHz short-range environments (see Sect. 4 for details).

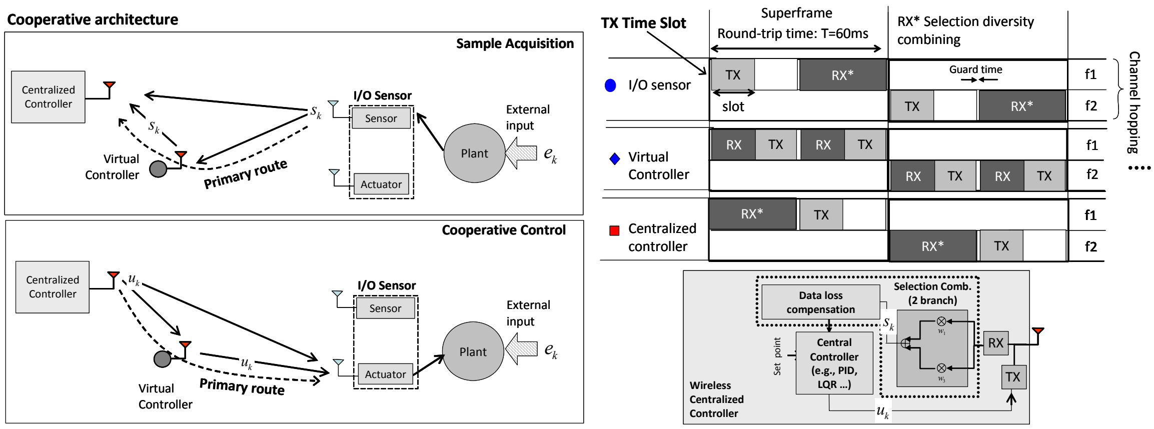

Fig. 2. Framing structure and timed-token message passing over the cooperative transmission architecture.

closed-loop control systems. The proposed architecture depicted in Fig. 2 consists of three components. The *I/O sensor* is the low power input/output field instrument that interacts with the plant behavior. The *centralized controller* manages a low-power radio interface for two-way communication with the remote I/O sensor and acts as a translator over the wired network. The *virtual controllers* are the additional infrastructure and take the dual role of cooperatively receiving the plant observations from I/O sensor and cooperatively transmitting control messages replacing the centralized controller when its direct link with the actuator experiences any degradation. The framing structure depicted in Fig. 2 (right-side sub-figure) refers to a system deploying $M = 1$ virtual controller with guaranteed cycle times $T_{\mathrm{RT}} \geq 50ms$. Extension to an arbitrary number M of virtual controllers is straightforward.

A. Cooperative network architecture

A sequence of messages is continuously transmitted by a *source* node S to a *destination* node D over an optimal "connection oriented" unicast route path $\mathcal{R}$ (primary route) that involves M intermediate virtual controllers relaying data to destination D. Source node S and destination node D take the role of I/O sensor and centralized controller for uplink, while their roles are reversed over downlink. The use of this cooperative architecture introduces redundancy during multi-hop message passing and implements a chain of consecutive cooperative transmissions [7]. At time slot $\#1$ the process observation is originated from I/O sensor source S and relayed at time slot $\#2$ from virtual controller node and so on. Similarly, after the destination is reached the same message propagation is initiated now by the centralized controller acting as source node for backward propagation of the feedback control message. In general, for each transmitting node $k \in \mathcal{R} \diagdown D$ there are up to d subsequent nodes in the route that are overhearing ($d = 2$ in the single virtual controller example). From receiving link, the k-th receiver has up to d copies of the same message during d subsequent time slots that experience statistically independent fluctuations of the received signal strength and can be incrementally combined to exploit the *cooperative diversity* order of d.

B. Superframe structure and control session

As shown in Fig.2 time division duplex system is employed to separate uplink and downlink. Transmissions are organized into superframes of $T = 60ms$ consisting of time-slots separated by guard times with a variable duration that depends on the required cycle time. A closed-loop control session starts with the transmission of measurement s_k and stops when the feedback control u_k is received and applied to the plant: this time must equal the round-trip time, here $T_{\mathrm{RT}} \geq 50ms$. To avoid bursty errors over consecutive loops, channel frequency hopping (FH) is implemented over consecutive closed-loop sessions. FH is commonly adopted in industrial communication as it is less susceptible to interference and also provides some additional protection against eavesdroppers. Physical access to wireless medium is based on slotted ALOHA where carrier sensing is performed before any transmission attempt to avoid cross-tier interference from external devices operating on the same frequencies (e.g., WiFi, Bluetooth).

C. Medium Access Control sub-layer

Medium access control uses a timed-token passing protocol on top of the multi-hop cooperative network architecture described in Sect. 3. Timed-token protocol has been also proposed to enforce real-time behavior on wired/wireless PROFIBUS networks and industrial Ethernet networks, overriding the native collision based multiple access. During MAC configuration, the network is organized into a logical *primary ring* connecting the I/O sensor to the centralized controller and viceversa. Primary ring is a two-way routing path connecting the controller with I/O sensor through the virtual controller. Routing path for $M > 1$ can be computed using existing standard routing protocols [7]. Each device belonging to the control loop has knowledge of its predecessor and successor along the primary ring. In the next step the cooperative links are configured on each device based on the selected degree of cooperative diversity d. Medium access control assigns to devices one time slot (TX Time Slot) for transmission and up to d time slots (RX Time Slots) for receiving redundancy over the virtual multiple links in uplink and downlink. A token information is multiplexed with information data and visits all the devices on every closed-loop session to synchronize cooperative transmissions. Token holding time is bounded to the duration of one time-slot to satisfy the round trip delay requirement T_{RT}.

A necessary prerequisite to guarantee a sufficient high quality of service during process control is the stability of the token passing procedure along the logical ring in the presence of transmission errors [12]. As depicted in the example of Fig. 2 (at bottom), the *selection combining* technique [7] allows each receiver to decode the message copy originated from the link that experienced the highest instantaneous RSS. Purpose of selection combining is to jointly enforce the real-time constraint and stabilize token passing by avoiding the use of error control methods based on explicit acknolwedgements.

IV. Wireless critical control: experiments

In the proposed experimental set-up the cooperative network specifics are implemented over battery-powered micaz motes based on the low-power single-chip 2.4 GHz IEEE 802.15.4 compliant CC2420 [8] with radio transmit power set to $P_T = 1mW$ and HW security AES-128 compliant. The RSS indicator (RSSI) is used to assess link quality for selection combining. According to the IEEE 802.15.4 standard, the RSSI provides an estimate of the signal power by averaging over 8 consecutive offset quadrature phase-shift keying (O-QPSK) symbols. RSSI is quantized using 8 bit/sample and periodically stored in the CC2420 RSSI_VAL register [8]. FH is performed over consecutive closed-loop sessions in exchange for an additional latency of $3ms$ for on/off radio switching.

Centralized controller is equipped with a low-power 8 bit AVR microcontroller implementing a proportional linear state-feedback controller such that $\mathbf{u}_k = \mathbf{P}\hat{\mathbf{x}}_k$ where $\hat{\mathbf{x}}_k = \mathbf{C}^{-1}\mathbf{s}_k$ while proportional feedback gain matrix $\mathbf{P}$ is designed to achieve the desired closed-loop pole locations. The evaluation of other control policies like proportional integral derivative (PID) are out of the scope of this paper. Enhanced control applied by virtual controllers employs a data loss compensation function such that missing process states are estimated by $\hat{\mathbf{x}}_k = \mathbf{C}^{-1}\hat{\mathbf{s}}_{k|k-1}$ with $\hat{\mathbf{s}}_{k|k-1}$ being the linear mean-squared error (LMMSE) predictor of missing sample $\mathbf{s}_{k|k-1}$. To simplify the experimental scenario, each micaz mote takes the dual role of input and output field instrument: the AVR microcontroller is used to emulate transducer and actuator functions by generating simulated process observations obtained from the discrete-time state-space plant model in (1). Observations $\mathbf{s}_k = \mathbf{x}_k + \mathbf{n}_k$ provide a noisy representation of the process states and are encoded before radio transmission using 16 bit/sample.

An additional metric to open loop probability P_c used to evaluate process stability is

$$P_{stability} = \Pr[\|\mathbf{x}_k - \tilde{\mathbf{x}}_k\| \leq \delta] \quad (4)$$

that measures the probability that the deviation of process states $\mathbf{x}_k$ from the stable set-points $\tilde{\mathbf{x}}_k$ i.e., caused by packet losses, lies below an accuracy parameter $\delta > 0$. This factor δ indicates a critical condition for HW instrumentation that might cause costly losses for the plant operator.

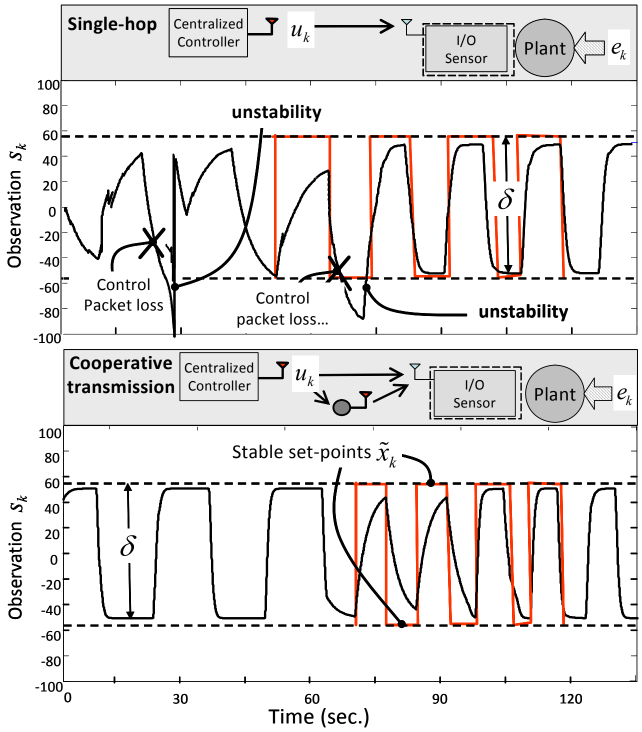

Fig. 3. Example of wireless process control by single-hop (top) and cooperative networking (bottom). Process observations are taken from simulated plant model. External input (red lines) superimposed to data.

An example of a single-hop (on top) and of a cooperative based (at bottom) closed-loop control is depicted in Figure 3: purpose is to assess process stability by visual inspection of plant variables with respect to accuracy threshold δ. In this example the noisy observations $s_k \in \mathbf{s}_k$ of one process state are visualized over a time window of 150 sec. To emulate a non-stationary disturbance, external random input $e_k \in \mathbf{e}_k$ (1) in solid red lines periodically switches among two set-points $\tilde{x}_k := \{58, -58\}$ with randomly varying period ranging from 10 to 20 sec. Stable set-points $\tilde{x}_k \in \tilde{\mathbf{x}}_k$ are indicated by dashed lines. In this example, the use of a single-hop network architecture is not sufficient to guarantee stability while the cooperative architecture provides a clear advantage.

For the experiments, the considered indoor environment consists of two adjacent rooms separated by a wall with 10cm thickness. Up to 7 people were moving inside rooms and this causes random fluctuations of radio signals. For all devices the antenna height[2] from ground is 1m, the harsh radio environment is made of metallic objects (e.g., cabling, tubes, metallic structures etc...) that cause additional attenuations. Centralized controller sends control messages to the I/O sensor placed in an adjacent room at distance 16m. This specific setting is designed to assess the impact of NLOS propagation on closed-loop control performance. For the proposed cooperative architecture, we considered the deployment of a single ($M = 1$ with diversity $d = 2$) virtual controller. Performance of single-hop and multi-hop architecture are also

[2]This is a worst case scenario as compared with typical installation designs that recommend 2m height from ground.

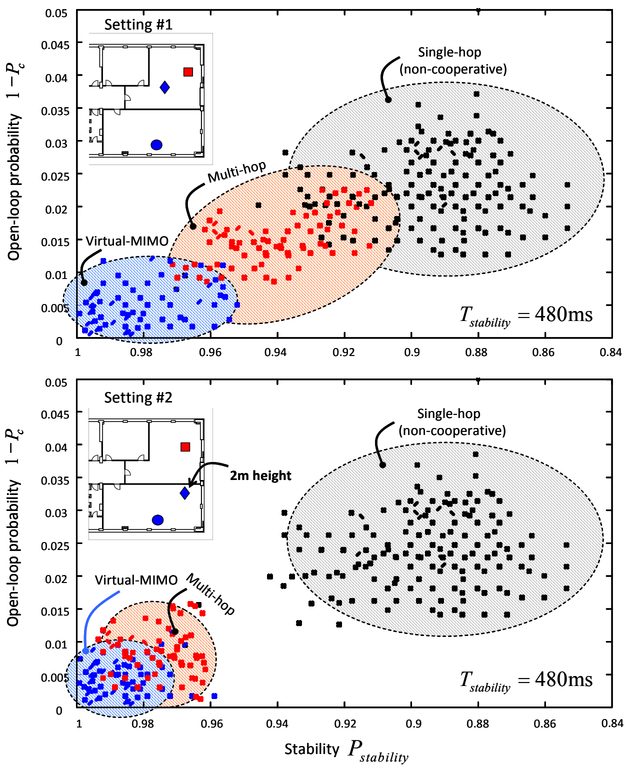

Fig. 4. Closed-loop control performance with stability interval $T_{stability} = 480ms$ (corresponding to $N_{stability} = 8$ consecutive control message losses). Each point maps to an open-loop probability $1 - P_c$ and stability $P_{stability}$ computed over 20 minutes of real-time control. Network topology "setting #1" is depicted in top-figure. The case for optimal deployment of the virtual controller is shown in "setting #2" at bottom.

evaluated: multi-hop requires the installation of a wireless repeater that implements decode and forward relaying. In the considered settings each new observation is acquired by I/O sensor on every $T_s = 60ms$, while cycle time $T_{\mathrm{RT}} > T_s$ is $T_{\mathrm{RT}} = 50ms$. Closed-loop control stability is evaluated over the state-space discrete time plant model characterized by open and closed loop poles $0.85 \pm 0.625j$ and $0.85 \pm 0.5j$, respectively. Analysis over the considered process shows that up to $N_{stability} = 8$ consecutive control message losses, corresponding to a *stability interval* $T_{stability} = N_{stability}T_s = 480ms$, are still tolerable in practice for stabilizing system dynamics. Instead, any link interruption with duration larger than $T_{stability}$ causes the process to become unstable.

Performance of closed-loop control are depicted in Fig. 4 for the considered plant model. For each setting, continuous real-time control is tested over a period of 5 days on average. Each point maps to the average open-loop probability $1-P_c$ with P_c defined in (3) and the process stability $P_{stability}$ (4) observed over a time window of 20 minutes. Tolerable deviation from stable set-points is based on feedback gain and chosen here as $\delta = (1+\varsigma) \times \max|\tilde{x}_k|$ with $\varsigma = 1/2$ so that $P_{stability} = 1$ for $P_c = 1$. In Fig. 4 we compare single-hop, multi-hop and cooperative settings configured with a single virtual controller. In top figure virtual controller is deployed in the same room of the centralized controller (setting #1). This case is often typical in industrial settings where the I/O sensor is deployed in hazardous areas and require ATEX or IP66/67 certification while the installation of additional infrastructure in the same area might be not allowed. In bottom figure a wireless repeater is deployed in the same room of I/O sensor (setting #2) as this is the best choice for network planning to minimize the packet loss probability over the two-hop route. For a required stability $P_{stability}$ ranging between 98% and 99%, the tolerable open-loop probability P_c must lie below 10^{-2} ($P_c > 0.99$) for both settings. Only the proposed cooperative architecture can guarantee such a high level of reliability. The multi-hop architecture is highly sensible to relay deployment as accurate network planning (if allowed) provides significant performance improvements as observed in bottom Fig. 4.

V. Concluding Remarks

The installation of wireless control networks in oil&gas refinery plants is expected to give significant cost/logistic savings in several applications. The most promising technologies to support next generation wireless critical process control systems are outlined. It is proposed a cooperative network architecture to emulate transmission and reception of data on a distributed network for tight closed loop process control applications. A proprietary cooperative link-layer protocol has been developed on top of IEEE 802.15.4 compliant PHY/MAC layer architecture designed for low-power consumption. Cooperative transmissions guarantee a robust two-way communication between the controller and the I/O sensor to guarantee process stability with cycle time of 50ms. Preliminary experimental results clearly suggest that the use of cooperative architectures is a mandatory roadmap to enable cable-replacing in future systems.

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