Proposal and Communication Scheme for a Wireless Networked Control System Coordination Agent

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Abstract

Wireless networked control systems have begun to gain acceptance during the last decade, largely due to the increased flexibility and lower costs they promise to provide. The pace of application has been held back, however, by the reluctance of industry to make the accommodations necessary to allow wireless paths to be incorporated in process control loops, thus limiting the potential applications and benefits of wireless systems. The problem is that there are conflicts between maintaining the performance (and particularly stability) of a control loop, which can be degraded by slow data rates and delays in a wireless path, and the usual objectives in managing a wireless sensor network, namely freedom to configure the network to maximize efficiency and to adjust data rates in the network to conserve energy consumption in the network nodes, which are very often battery powered.

We are working to address this conflict by developing a wireless networked control system coordination agent, as part of an intelligent supervisory control system, which will grant the wireless sensor network gateway as much latitude in meeting its objectives as possible while maintaining the performance of control loops that incorporate wireless paths.

1 Introduction

During the past two decades, a large amount of research has been done on distributed control systems that incorporate wireless sensor networks, or what are called Wireless Networked Control Systems (WNCSs). That interest can be traced to the many advantages achieved by eliminating the restrictions of traditional point-to-point wired control architectures, such as a reduction in wiring, rapid deployment, flexible installation, fully mobile operation, and improved freedom in placement of controllers [1] [3] [4] [5]. In such systems, distributed sensors, controllers, and actuators are exchanging information over a communication network.

New developments in wireless networked control allow engineers to support a number of control applications that were previously difficult to realize or afford. Due to the rapid development of Micro Electro Mechanical Systems (MEMS) and wireless communication devices, engineers can integrate small sensors, actuators, processors, batteries, and wireless communication devices into what are called wireless sensor and actuator networks, or, more simply, wireless sensor networks (WSNs). The WSN nodes can then be distributed in large numbers to self-organize into networks that serve a wide range of purposes, including off-shore petroleum applications, environmental monitoring, industrial process control and intelligent systems for any application. Improved technology and stricter requirements makes the development of WNCSs more difficult, however. Part of the problem arises from inflexibility in the imposition of strict requirements on data rates, jitter, latency and data loss to ensure control system performance on one hand [3] [5], and effective protocols for WSN robustness and efficiency [1] [4] on the other.

Our primary interest in WNCSs is for Petroleum Applications of Wireless Systems (PAWS[1]), a major research program at Cape Breton University (CBU, the project lead dealing with WSNs [2]), the University of New Brunswick (UNB, focussed on Intelligent Control and Asset Management or ICAM [9]), the College of the North Atlantic (CNA, which supports a pilot plant for petroleum processing [6]) and several industrial partners.

Developing a distributed control system over a wireless sensor network is a challenging task because it is necessary to satisfy pressing requirements from both fields, communication networks and control systems. The stability of a closed-loop system with wireless links (sensor-to-controller, controller-to-actuator) is one of the most important requirements in industrial control systems. Although

[1]The Petroleum Applications of Wireless Systems project is supported by the Government of Canada, through the Atlantic Innovation Fund (AIF).

modest data rates, network delay, packet loss, and jitter may generally be acceptable in communication networks, there are strict limits as to what can be accepted in the case of closed-loop control over wireless networks. In WNCSs the network design objectives must include optimizing control performance, or at least maintaining stability-related constraints such as maximum acceptable percent overshoot. On the other hand, from the wireless sensor network perspective it is desirable to conserve node battery power and to have complete flexibility to configure the network to promote the efficient use of resources; therefore, slower data rates and more delay may be accepted to achieve these goals. Thus, there are distinct tradeoffs between network communications and controller performance.

We are addressing this problem by developing a Wireless Networked Control System Coordination Agent (WNCSCA). The main responsibility of the WNCSCA is *data rate* and *path delay management*, both of which have a major impact on controller performance, the stability of the closed-loop control loop over the wireless sensor network, and the energy consumption of the WSN nodes. Node energy conservation is a critical issue in wireless sensor networks for node and network life, as the nodes are usually powered by batteries, and in many cases the replacement of these power sources is difficult, inconvenient, and/or expensive. Our WNCSCA will coordinate with ICAM and the WSN gateway to allow as much network optimization and flexibility as possible based on the requirements of the WNCS.

2 WNCS Coordination Agent

Our WNCSCA is being implemented as a part of ICAM, which is a multi-agent intelligent supervisory system for petroleum processing facilities [9]. This agent will serve to mediate between the ICAM system and the Gateway of CBU's Wireless Industrial Sensor Network Testbed for Radio-Harsh Environments (WINTeR). WINTeR is an open-access, multi-user experimental testbed, currently under development by CBU under the PAWS project, to support implementation and evaluation of wireless sensor networks for industrial applications in radio-harsh environments [7]. WINTeR now supports process simulations with wireless in the loop; in the future the goal is to interface WINTeR with actual industrial processes. There are two process simulators currently linked to WINTeR, one a high-order, highly complex model of the CNA pilot plant [6] which has five control loops and is extremely challenging to work with, and the other a simple model of a jacketed continuous stirred-tank reactor (JCSTR) [8]; the JCSTR has been chosen and implemented as a process simulator to better allow us to study issues related to the stability and performance of control systems over a wireless sensor network. This will facilitate development of the WNCSCA, thus forming an important enabling technology for the use of WSNs in process control applications.

During the operation of the ICAM system, its agents impose different specifications or requirements from the WSN to complete their functions properly. For example, some agents require different data rates from specific sensors and actuators in specific regimes, such as start up mode, set-point change mode and steady state mode for supervising and monitoring the plant. During start up mode, the initial process variable transients must decay under closed-loop control, so appropriate data rates and path delays must be imposed. Once the process reaches the desired steady-state set-point the model identification agent may perturb the plant with pseudo random signals (to excite all the modes in the plant), gather data and apply its model identification algorithm, perhaps needing a different data rate than before. After that, the process may remain settled in steady state, in which case loops can be opened[2] and data rates reduced so ICAM can monitor the process; as long as there are no disturbances or set-point changes slow sampling can continue and the Gateway can manage its operations freely and conserve energy accordingly. In many industrial systems a process may be in steady state for long periods of time, with infrequent set-point changes requiring closed-loop control, so this strategy will allow the WSN to managed in a more optimal way much of the time.

In summary, the various modes of operation require tighter or looser constraints on data rates and path delays; the WNCSCA mediates between ICAM and the Gateway to allow both the control system and the WSN to meet their objectives as flexibly and well as possible. The interface between the ICAM system and the Gateway of WINTeR is portrayed in figure 1.

2.1 WNCSCA Architecture

The functions and roles of the WNCSCA can be identified in different layers or levels, based on their functionality, as follows:

- **Node level**: this is the lowest level of work for the WNCSCA, where it is involved in checking the total packet latency (path delay) over sensor-to-controller and controller-to-plant paths. The WNCSCA also controls the data rate (sampling period) for each sensor node, which also has a great impact on the energy consumption and the life time of the wireless sensor network.

- **Network level**: this is the middle level of the WNCSCA's activity, where it is involved in specifying conditions on the management of the *ad hoc* network such as the network configuration, network latency and connectivity.

- **Task level**: this is the highest level in the WNCSCA's effort, where it is involved in the user monitoring of

[2] Opening control loops momentarily to handle data drop-outs has been suggested in [3]; our strategy of opening control loops to alleviate strict control-related WSN constraints is new.

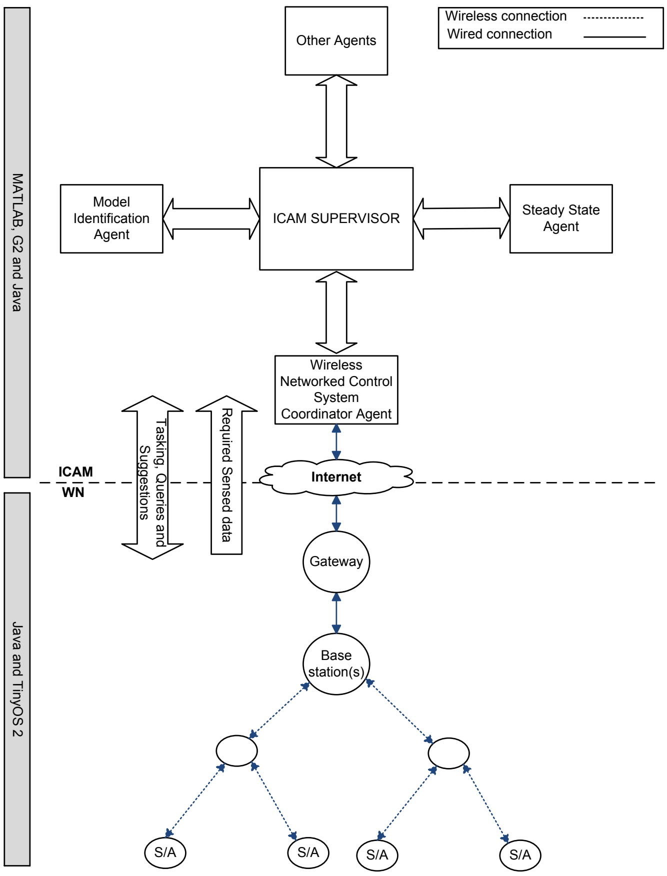

Figure 1. Schematic of the WNCS Coordination Agent interface with ICAM and WINTeR .

the wireless sensor network, performing stability analysis for the control system's loops and assigning and coordinating sensing tasks.

2.2 WNCSCA Objectives

The objectives of this agent are as follows:

1. Interface between the ICAM system and the Gateway of the wireless sensor network
2. Check the configuration of the WSN to determine whether or not it meets control-loop stability requirements
3. Manage energy consumption strategically, in partnership with the Gateway, by allowing reduction of the data rates for sensor nodes as much as possible without destabilizing control loops
4. Monitor the process state to determine its behavior (mode), e.g., are the process variables in steady state or transient conditions; this information is provided by ICAM's Steady-state Agent
5. Perform stability analysis based on the path delay and sampling time of the WSN; based on that analysis the WNCSCA will accept or reject the WSN configuration.

3 WNCSCA Communication with ICAM and the WSN Gateway

The WNCSCA interfaces with the ICAM Supervisor and the Gateway of the WSN at CBU using a new communication scheme. The communication approach is being implemented by invoking TCP/IP Java sockets in MATLAB. The communication scheme can be divided into three phases, as follows:

3.1 Booting and Initialization Phase

- **Booting**: during the booting process the three entities (the ICAM Supervisor, WNCSCA and WINTeR, represented by the Gateway) start working for the first time. The operator starts operation via the ICAM Supervisor by sending a **`Start`** message to the WNCSCA, as shown in figure 2. Each entity tries to make sure that the other partners are there (existing and alive) by exchanging **`Wake Up`** and **`Hello`** messages.
- **Initialization**: in general terms, during the initialization process the WNCSCA commands the Gateway to assess the health of the WSN (see which nodes are operational, check battery levels) and generate a configuration for the WSN; then the WNCSCA will check the proposed configuration based on a stability analysis for the closed-loop control system over the wireless sensor network, taking into consideration the sampling rate of sensors and the time delays for the packets in the wireless sensor network. Based on that analysis, the WNCSCA will accept or reject the proposed configuration from the Gateway; if rejected, the Gateway must try again, either increasing the data rates or decreasing the path delays (number of hops), as suggested by the WNCSCA. The details of this process are discussed below.

After finishing the booting phase The ICAM Supervisor and WSN Coordination Agent start defining and initializing variables. ICAM receives or requests the set points for the process and sensor/actuator node information from the operator. Then, the WNCSCA sends a request to the ICAM Supervisor asking for a plant model. (The plant model is a 2×2 matrix which contains four scalar transfer functions describing the linearized process and its controllers, based on the JCSTR linearized model which will be retrieved from a data base according to the set point given by the operator.)

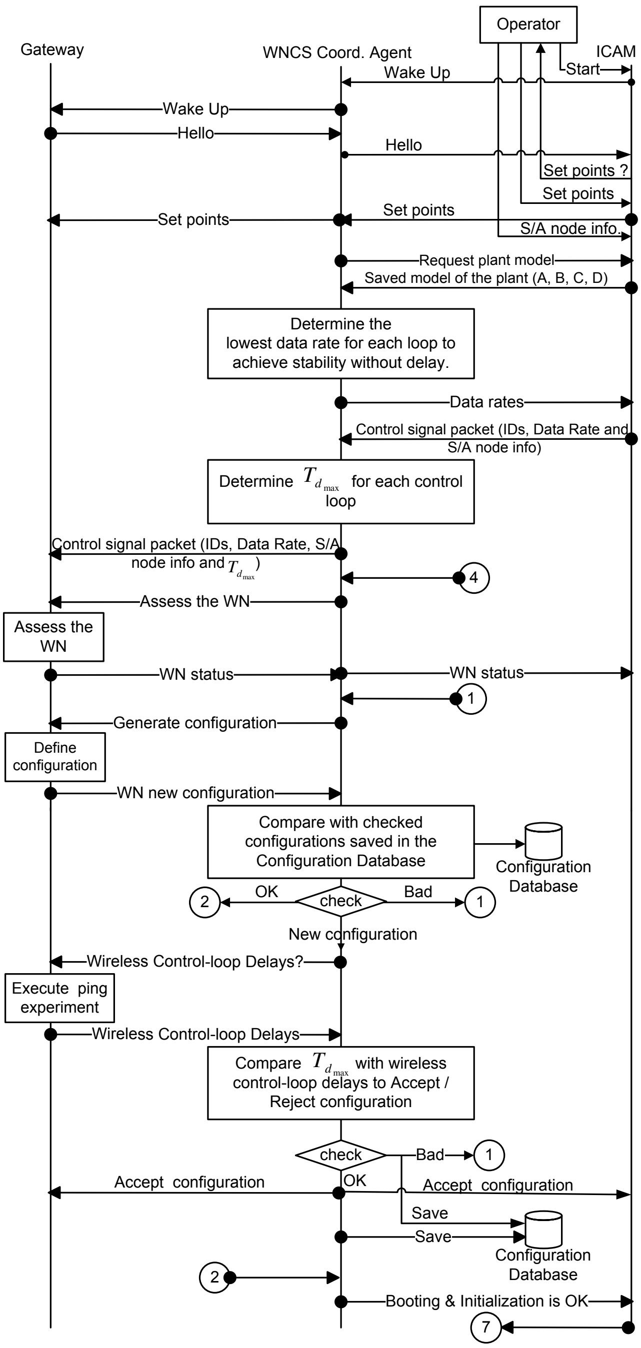

Figure 2. Communication scenario for WNCSCA interface with ICAM and the Gateway, Booting and Initialization Phase.

Then the ICAM Supervisor sends a packet to the WNCSCA which contains the address of each sensor and actuator node, the data rate for each sensor, and sensor/actuator nodes pair information (each control loop is associated with one sensor/actuator pair). The WNCSCA sends a request to the Gateway asking it to assess the WSN by using its Energy-Efficient Protocol (checking the connectivity between each node, the battery level, the shortest paths, the most reliable path for the packets and the general health of the WSN). After the Gateway finishes the WSN assessment process, it is asked to define a configuration based on the acquired information from the assessment process. Once the Gateway obtains a WSN configuration from the Base Station, it forwards that configuration to the WNCSCA to check for closed-loop stability.

Before carrying out that operation, the WNCSCA compares the proposed configuration with the existing "checked configurations" saved in the Configuration Database. This operation will save much time: If the proposed configuration already exists in the Configuration Database the WNCSCA can check whether that configuration is `Ok` (meets the stability requirements of the closed loop system over the WSN) or `Bad` (violates stability conditions), and accepts or rejects it accordingly. If accepted, then the WNCSCA notifies ICAM and the Gateway and switches to Normal Operation Phase; if it is rejected, again the WNCSCA notifies ICAM and the Gateway and it waits for a new proposed configuration from the Gateway. If it is not in the Configuration Database then it needs to be checked, as discussed below. The associated communications and logic are shown in figure 2. The WNCSCA will keep track of all acceptable (`Ok`) configurations and invalid (`Bad`) configurations in the Configuration Database; this has the potential to save much time and effort in checking proposed configurations, especially as the system is repeatedly used and the Configuration Database grows.

The New Configuration Checking procedure is carried out as follows: The WNCSCA performs process simulation tests to determine the lowest sampling rate for each sensor/actuator pair, to achieve acceptable control system performance while reducing the energy consumption as much as possible. The WNCSCA also needs to know the delays which the packets will encounter over the WSN paths (chains of nodes) involved in the closed-loop control system during their journey from the sensor nodes to the Gateway and Gateway to actuators (chain delay), to be able to decide whether to accept that topology or not. This can be done by running a "ping" experiment through the assigned paths by using the proposed configuration. Then, the Gateway responds to that request by carrying out the tests and sending the delays for each control-loop chain. The WNCSCA will compare that delay with the real delay which was sent by the Gateway and make the final decision whether to accept that topology or not. The WNCSCA's accept/reject decision for that configuration will be sent to the Gateway and ICAM system, and the configuration and decision stored in the Configuration Database. Once an acceptable configuration is determined via the logic shown in figure 2, the WNCSCA switches into the Normal Operation Phase.

3.2 Normal Operation Phase

Normal operation of the WNCSCA is focused on monitoring the WSN and maintaining an acceptable control loop stability margin (defined by the percent overshoot of the corresponding step response). At the beginning of this phase, the ICAM Supervisor commands the Steady State Agent to perform a steady state test, to see whether the controlled variables are operating in the steady or transient state. If the controlled variables are operating in steady state, the WNCSCA checks if this is the first time for the controlled variables to operate in that state or not; in this way it detects the beginning of the steady state period for that controlled variable. If the state is **`Transient`**, the WNCSCA goes to execute point 5 in figure 3, otherwise if the state is **`Steady`**, the WNCSCA sends a **`Reduce Sampling Rate?`** message asking the Gateway if it wants to reduce the associated sampling rate. If the answer of that question is **`No`**, the WNCSCA goes to execute point 5, but if the Gateway sends a **`Yes`** message to the WNCSCA then it calculates the reduced data rates, sends an **`Open the loops`** message to the ICAM Supervisor (assuming that the process control variables can be maintained at the same values without changing), and tells the Gateway to reduce the data rate, to permit monitoring the process variables while reducing energy consumption.

If the controlled variables are operating with state = **`Transient`**, then the WNCSCA also checks if this is the first time for the controlled variables to operate in that state, i.e., it detects the beginning of the transient period for that controlled variable. If the transient state is not just beginning, the WNCSCA goes to execute point 5, otherwise the WNCSCA commands the Gateway to revert to the normal sampling rate (NSR). At this time, the Gateway applies the NSR to the sensors, then it notifies the WNCSCA which tells ICAM to close the control loop(s). The Gateway always sends the sensed data (e.g., levels and temperature values of the mixture inside the reactor of the JCSTR simulator) to the WNCSCA which also sends this sensed information to the ICAM Supervisor for process understanding and monitoring. The ICAM Supervisor also invokes the NDDR Agent and the FDIA Agent to perform their tasks during normal operation.

During normal operation, the Gateway may tell the WNCSCA that there are newly installed nodes, and the WNCSCA will relay that information to the ICAM supervisor. Then, the Operator must supply information which distinguishes between new sensor and/or actuator nodes, and identify any changed sensor/actuator loop pairs. The WNCSCA also forwards that information to the Gateway, and the Gateway may call for a new network configuration, which is handled as before.

Finally, the ICAM supervisor may decide that an “abnormal operation” is needed, i.e., a procedure that requires unusual resources, such as data rates that differ from normal; if so, it sends an **`Abnormal`** message to the WNCSCA and the WNCSCA will go execute the abnormal operation phase (figure 4).

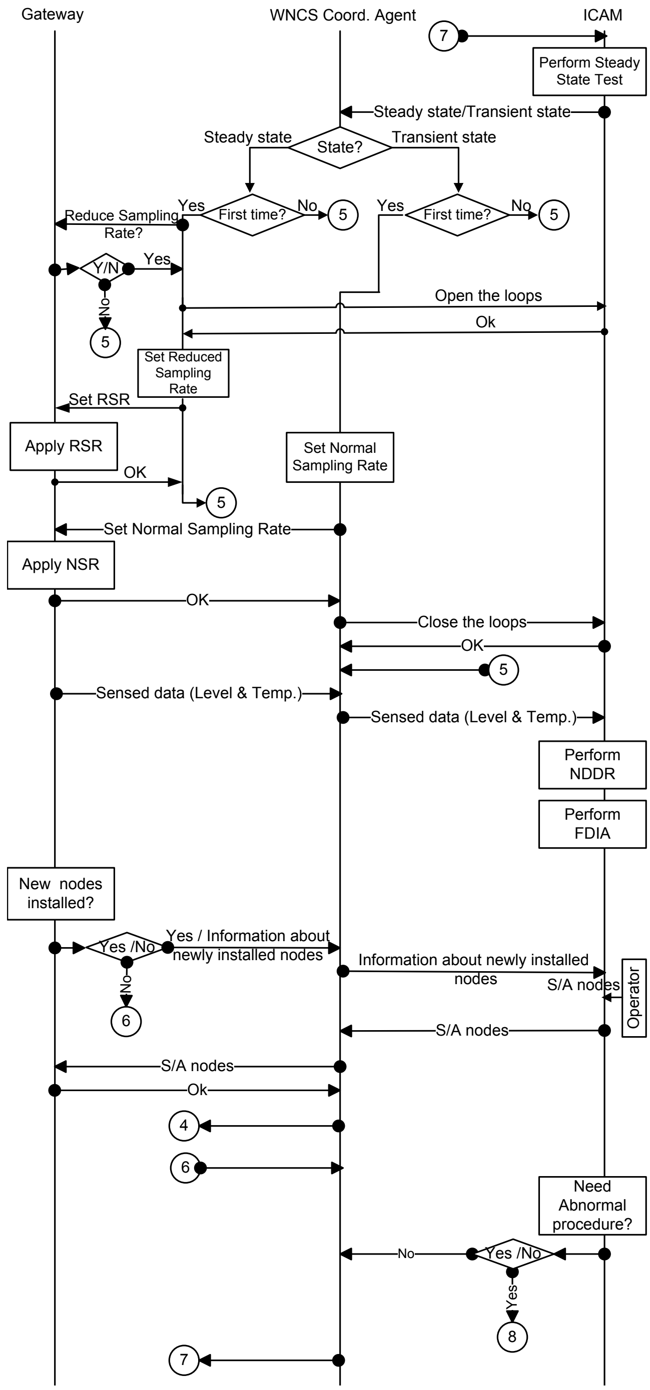

Figure 3. Communication scenario for WNCSCA interface with ICAM and the Gateway, normal operations.

3.3 Abnormal Operation Phase

This phase starts whenever the ICAM Supervisor decides that it needs to perform a procedure that has an above-normal requirement, such as a higher data rate. If so, the ICAM Supervisor again sends an **`Abnormal`** message to the WNCSCA, asking to perform that task, as shown in figure 3. The WNCSCA, in turn, asks the Gateway if it is possible to, for example, increase the data rate. If the answer to that question is **`NO`**, the WNCSCA will go to point 2 in the communication scenario, but if the answer is **`YES`** the WNCSCA notifies ICAM and the ICAM Supervisor sends a control signal packet to the WNCSCA which contains the address of each sensor and actuator, along with the data rate for each. The WNCSCA then relays this information packet to the Gateway, to apply this new requirement.

Once the "abnormal procedure" is done the ICAM Supervisor will notify the WNCSCA that it may return to normal operation; that is the end of this phase.

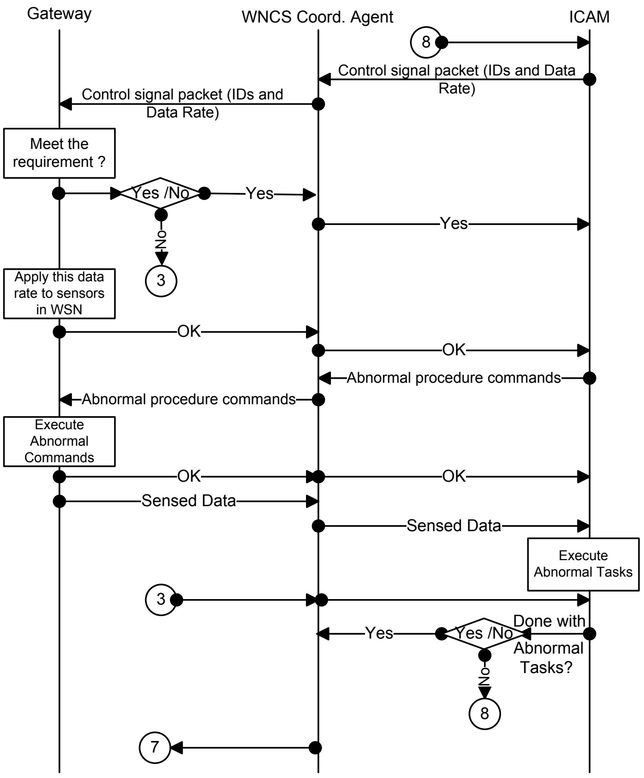

Figure 4. Communication scenario for WNCSCA interface with ICAM and the Gateway, abnormal operations.

4. Conclusion

The communication scheme described above constitutes the preliminary design and specification for a Wireless Networked Control System Coordination Agent to manage the potential "conflicts of interest" between industrial control systems requirements and objectives of a typical wireless sensor network gateway protocol. The amount of freedom given to the wireless sensor network gateway to meet its objectives *must* depend on the current state of the control system loops that incorporate wireless paths, and the communication scheme described here is designed to maximize that freedom. This article represents the first phase of development of such a wireless sensor network coordination agent.

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