A Safe Communication Scheme for an Intelligent 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 of control loops, which can be degraded by slow data rates and delays in wireless paths, and the usual objectives in managing a wireless sensor network, namely freedom to configure the network and to adjust data rates at will, to maximize efficiency and to conserve energy consumption in the network nodes, which are very often battery powered.**

We address this conflict by developing a new[1] component for use in industrial control systems, called a Wireless Networked Control System Coordination Agent. This agent is designed to be part of an intelligent supervisory control system, and to 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, thus adding to the safety and reliability of future wireless networked control systems. In this discussion we deal with data rates and control-loop path delays as the two primary concerns; in the future we plan to extend the scope of this agent to handle more issues, such as jitter and wireless sensor network loading effects (e.g., variation of path delays with changes in loading).

***Index Terms*—Wireless Sensor Networks, Wireless Networked Control Systems, Control System Performance, Safety, Reliability, Efficiency.**

I. 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 costs, rapid deployment, flexible installation, fully mobile operation, and improved freedom in placement of controllers [2] [4] [5] [7]. In such systems, distributed sensors, controllers and actuators exchange information over a wireless 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 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 make the development of WNCSs more difficult, however. Part of the problem arises from inflexibility in the imposition of strict requirements on data rates, latency and data loss to ensure control system performance on one hand [4] [7], and effective protocols for WSN robustness and efficiency [2] [5] on the other.

Our primary interest in WNCSs is for the Petroleum Applications of Wireless Systems (PAWS[2]) project, a major research program at Cape Breton University (CBU, the project lead dealing with WSNs [3]), the University of New Brunswick (UNB, focussed on Intelligent Control and Asset Management or ICAM [8], [9], [14]), the College of the North Atlantic (CNA, which supports a pilot plant for petroleum processing that

[1]A U. S. Patent disclosure is being prepared for the Wireless Networked Control System Coordination Agent described here.

[2]The PAWS project is supported in part by the Government of Canada, through the Atlantic Innovation Fund (AIF).

was modeled by UNB [10]) and two industrial partners, Asea Brown Boveri (ABB Canada, Dartmouth, NS) and Adaptics, Inc. (McLean, VA).

Developing a distributed control system over a WSN is a challenging task because it is necessary to satisfy pressing requirements from both fields: communication networks and control systems. The performance of a closed-loop system with wireless links (sensor-to-controller, controller-to-actuator) is one of the most important requirements for industrial control systems. Although modest data rates, network delays and packet losses 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 WSN 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 control system performance.

We addressed this dilemma by developing a Wireless Networked Control System Coordination Agent (WNCSCA). The main responsibilities of the current WNCSCA are *path delay* and *data rate management*, both of which have a major impact on controller performance over the WSN and on the energy consumption of the WSN nodes. Node energy conservation is often a critical issue in WSNs 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 coordinates with ICAM and the WSN Gateway to allow as much network optimization, flexibility and efficiency as possible based on the safety requirements of the WNCS. Note that we assume that the Gateway will be a powered node, with sufficient computational power and software to provide the functionality mentioned in this presentation.

II. WNCS Coordination Agent

Our WNCSCA was conceived 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 [11]). WINTeR is an open-access, multi-user experimental testbed, developed by CBU under the PAWS project, to support implementation and evaluation of WSNs for industrial applications. WINTeR supports process simulators with wireless in the loop. There are two process control simulators[3] currently linked to WINTeR for use in studying WNCSs, one a high-order, highly complex model of the CNA pilot plant [10] which has five control loops, and the other a simpler nonlinear model of a jacketed continuous stirred-tank reactor (JCSTR [12]) with two control loops (tank liquid level and temperature); the JCSTR has been chosen and implemented as a process simulator to better allow us to study issues related to the performance of control systems over a WSN. This has and will continue to 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 supervisory system, its agents impose different requirements or specifications on 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 of the dynamic modes in the plant), gather data and apply its model identification algorithm, perhaps using different data rates than before [6]. After that, the process may remain settled in steady state, in which case loops can be opened[4] 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 WSN Gateway can manage its data rates 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 be 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 WSN 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. We describe the WNCSCA communication scheme in this paper; in [13] we present and demonstrate the effective method and algorithms for determining the maximum allowable packet delays and minimum data rates that the WSN Gateway may utilize without excessively degrading the performance of control loops operating over the WSN when loops are closed. Specifically, we define *design percent overshoot* (% OS) as desirable performance and *acceptable* % OS as the limit

[3]The WNCSCA can coordinate with any industrial process, real or simulated, regardless of its characteristics.

[4]Opening control loops momentarily to handle data drop-outs has been suggested in [4]; our strategy of opening control loops during steady-state operation to alleviate strict control-related WSN constraints is new.

enforced by the WNCSCA; for example, the case presented in [13] corresponds to design % OS = 10, acceptable % OS = 25, which represents a case where fast response is more important than overshoot. More conservatively, one may use design % OS = 0, acceptable % OS = 10. The WNCSCA uses the nonlinear process simulator in an efficient way to determine the safety limits for acceptable % OS.

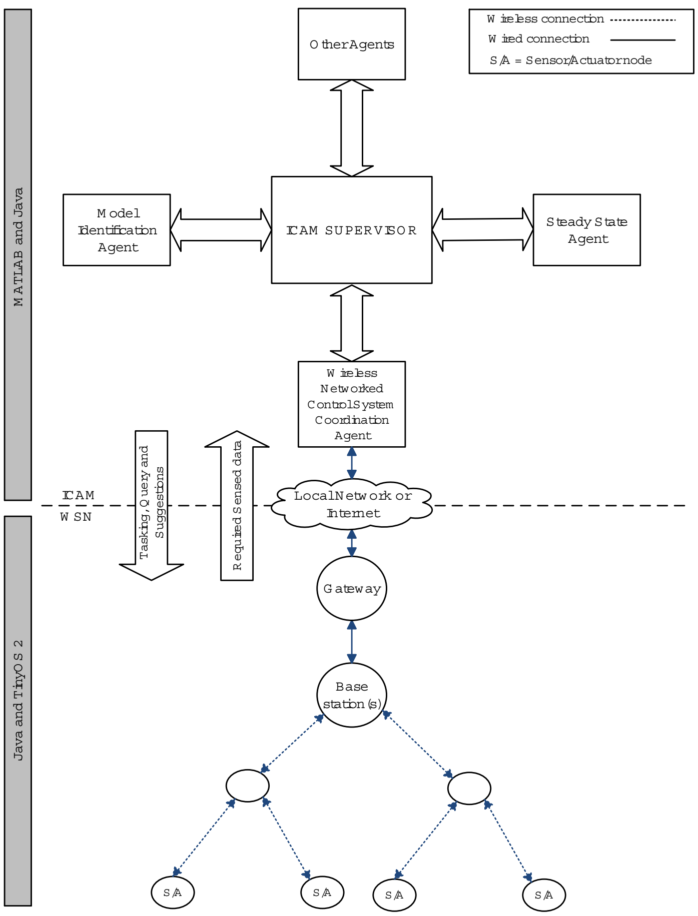

Fig. 1. Schematic of the WNCSCA interfaces with ICAM and WINTeR

A. 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 concerned with the data rate (sampling period) for each sensor/actuator node pair, which has a great impact on the energy consumption and the life time of the WSN.
- **Network level**: this is the middle level of the WNCSCA's activity, where it is involved in specifying constraints on the management of the *ad hoc* network, such as the network configuration, total packet latency (path delay) over sensor-to-controller and controller-to-plant paths, and connectivity.
- **Task level**: this is the highest level in the WNCSCA's effort, where it is involved in monitoring the WSN, conducting performance analysis for the control system's loops, and assigning and coordinating sensing and actuation tasks.

B. WNCSCA Objectives

The objectives of this agent are as follows:

1) Interface between the ICAM system and the Gateway of the WSN
2) Manage energy consumption strategically, in partnership with the Gateway, by allowing reduction of the data rates for sensor nodes as much as possible without degrading the performance of control loops
3) 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 (see [1] for more information about the Steady-state Agent)
4) Conduct control performance analysis based on the path delay and sampling time of the WSN; based on closed-loop path delays the WNCSCA will accept or reject a proposed WSN configuration, and based on the control mode, e.g., open- or closed-loop operation, the lowest acceptable data rates will be specified.

III. 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:

A. Booting and Initialization Phase

- **Booting**: During the booting process the three main 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[5] to the WNCSCA, as shown in figure 2. Each entity tries to make sure that the other partners are ready (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 connectivity) and generate a proposed configuration for the WSN; then the WNCSCA will check the proposed configuration based on a performance

[5] Actual messages are sent as integers; text is used here for clarity.

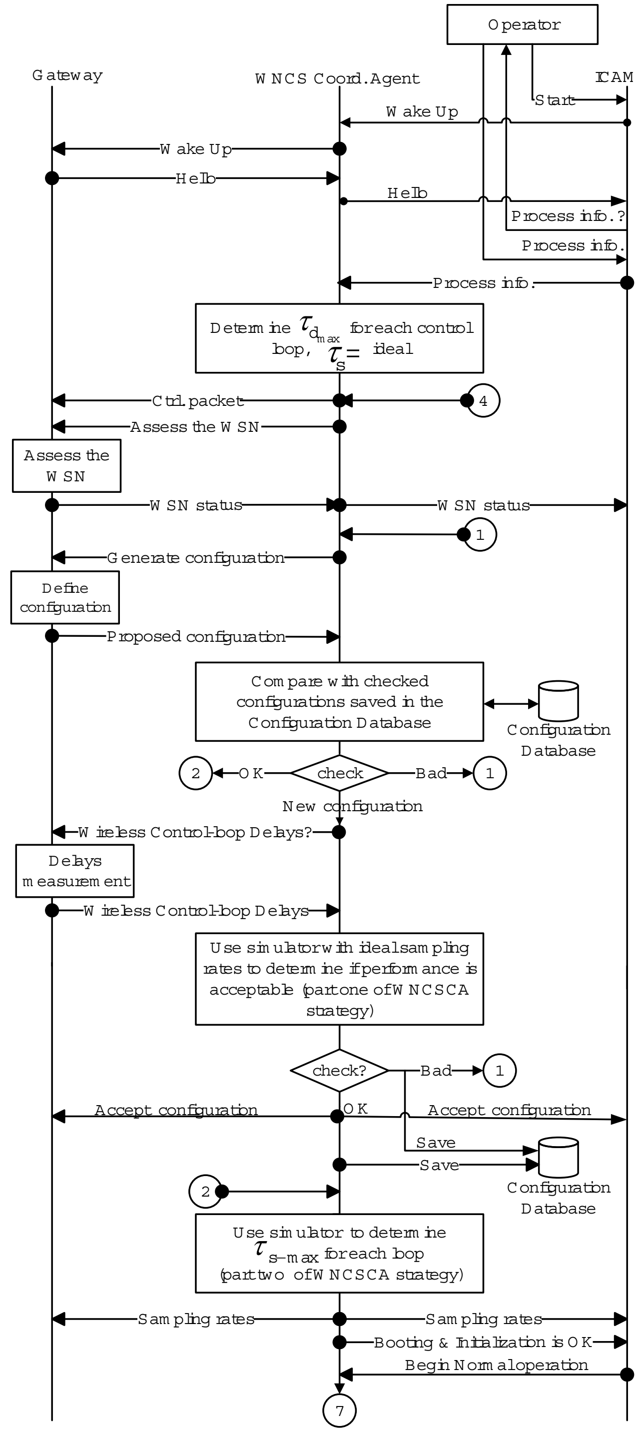

Fig. 2. WNCSCA communication scenario, Booting and Initialization Phase.

analysis for the nonlinear closed-loop control system over the WSN, taking into consideration the sampling rates of sensor/actuator pairs and the time delays for data packets in the WSN for paths in control loops. Based on that analysis, the WNCSCA will accept or reject the proposed configuration from the Gateway; if rejected, the Gateway must try again, decreasing the path delays (number of hops), as suggested by the WNCSCA. In the event that a suitable configuration cannot be found, the WNCSCA notifies ICAM, which in turn opens the control loops and raises an alarm. The details of this process are discussed below.

More specifically, after finishing the booting phase the ICAM Supervisor and WNCSCA start defining and initializing variables. ICAM receives the process identifier, the set points for that process, and sensor/actuator node information from the operator. Then, the WNCSCA sends a request to the ICAM Supervisor asking for **`Process info`**. Process information consists of the process or simulator to run (e.g, JCSTR), S/A node information (to identify the sensor and actuator node for each loop and provide ideal data rates), and set points to be used in the simulator. The ICAM Supervisor sends this packet to the WNCSCA; after this information is received, the WNCSCA runs experiments to determine the maximum time delays $T_{d_{max}}$ which will keep the wireless control loops performing acceptably.

Based on this, the WNCSCA sends a **`Ctrl. packet`** to the WSN Gateway, containing the S/A node and data rate information, and then 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 levels, the shortest paths, the most reliable paths for the packets and the general health of the WSN). After the Gateway finishes the WSN assessment process and reports, it is asked to propose a WSN configuration based on that information. Once the Gateway obtains a WSN configuration from the Base Station, it forwards it to the WNCSCA.

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 performance requirements of the closed loop system over the WSN) or **`Bad`** (violates performance requirements), and accept or reject it accordingly (taking into consideration a tolerance in the time delays, as this is a dynamic issue for the same configuration based on network loading). If it is **`OK`**, then the WNCSCA uses the process simulator to determine the minimum data rates for acceptable performance and notifies ICAM and the Gateway of that result so they may switch to Normal Operations Phase; if it is **`Bad`** then it is rejected; again the WNCSCA notifies ICAM and the Gateway and it waits for a new proposed configuration from the Gateway. Maintaining the Configuration Database 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.

On the other hand, if the proposed configuration is **`New`** (not in the Configuration Database) then it needs to be checked more rigorously. This procedure is carried out as follows: The WNCSCA requests that the WSN Gateway determine the actual control loop path delays, using (in order of preference) time stamps, 'ping' tests or multiplying the number of hops by the estimated delay-per-hop. If the actual delays are satisfactory, then 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. This process is described in detail in a companion paper [13]. The WNCSCA makes the final decision whether to accept the proposed topology or not, sends that decision to the Gateway and ICAM system, and stores the result in the Configuration Database. Once an acceptable configuration is determined via this logic, the WNCSCA switches into Normal Operations Phase. Again, an alarm will be raised if an acceptable WSN configuration cannot be found.

B. Normal Operations Phase

Normal operation of the WNCSCA is focused on monitoring the WSN and maintaining acceptable control loop performance (defined in terms of the percent overshoot of the corresponding loop step responses). 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. 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 a steady-state or transient period for the controlled variables. If the new state is **`Transient`**, then the WNCSCA sets the data rates to values required for acceptable closed-loop control (Normal Sampling Rates, NSR) and tells ICAM to close the loops; otherwise, if the new state is **`Steady`**, the WNCSCA tells ICAM to open the loops and sets Reduced Sampling Rates, RSR, so the Gateway can lower the S/A node data rates to be suitable for passive monitoring, including the detection of any subsequent start of **`Transient`** operation, thereby safely reducing WSN energy consumption as long as possible. Ideally, the RSR should permit other ICAM activities such as the invocation of the NDDR (Nonlinear Dynamic Data Reconciliation) Agent to remove outliers and data drop-outs, ensure that the process variables satisfy material and energy balance, and reduce the noise levels in the collected signals; and the FDIA (Fault Detection, Isolation, and Accommodation) Agent to perform its important task during normal operation. For more information about NDDR and FDIA see [1] and [6].

During normal operations, 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 S/A loop pairs. The WNCSCA also forwards that information

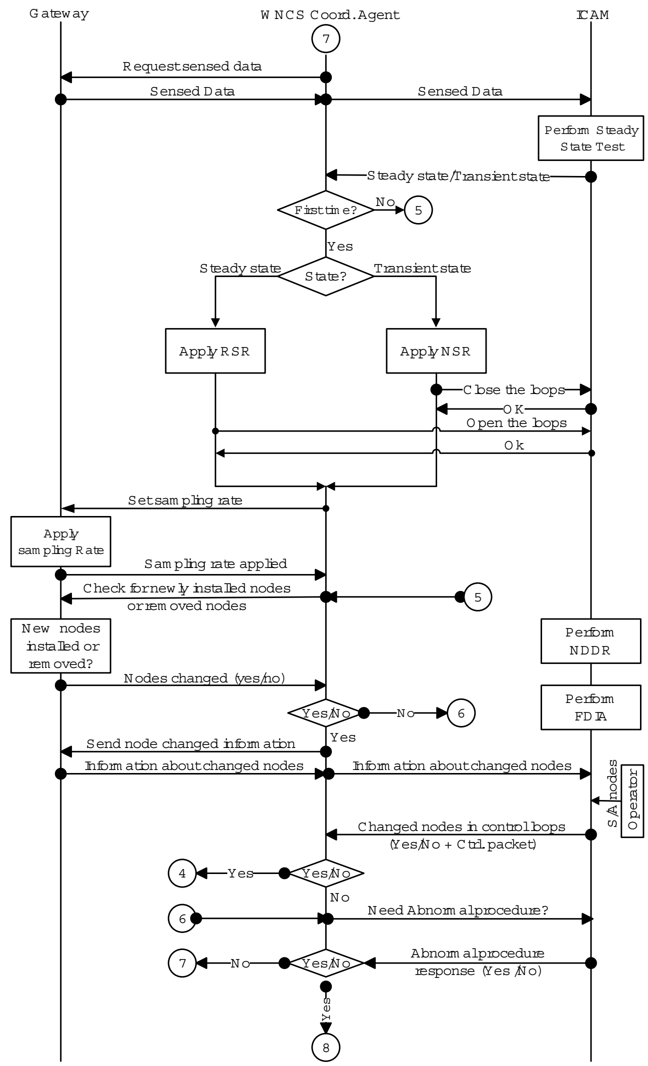

Fig. 3. WNCSCA communication scenario, Normal Operations Phase.

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 (NSR or RSR). The WNCSCA checks in every execution loop of Normal Operations; if so, ICAM sends an **`Abnormal Yes`** message to the WNCSCA and the WNCSCA will go execute the Abnormal Operations Phase (figure 4), otherwise looping in the Normal Operations Phase continues.

C. Abnormal Operations Phase

This phase starts whenever the ICAM Supervisor decides that it needs to perform a procedure that has non-standard requirements, such as higher or lower data rates. If so, the ICAM Supervisor responds to the **`Need Abnormal Procedure?`** message from the WNCSCA by replying **`Yes`** and sending the corresponding **`Ctrl. packet`** identifying S/A nodes and data rates, as shown in figure 4. 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 3 in the communication scenario to see if a different Abnormal Operation is desired, but if the answer is **Yes** the WNCSCA notifies ICAM that it can proceed. Sensed data is supplied to the ICAM Supervisor, as in normal operations but at possibly different data rates.

Once the "abnormal procedure(s)" are done the ICAM Supervisor will notify the WNCSCA that it may return to the Normal Operations Phase.

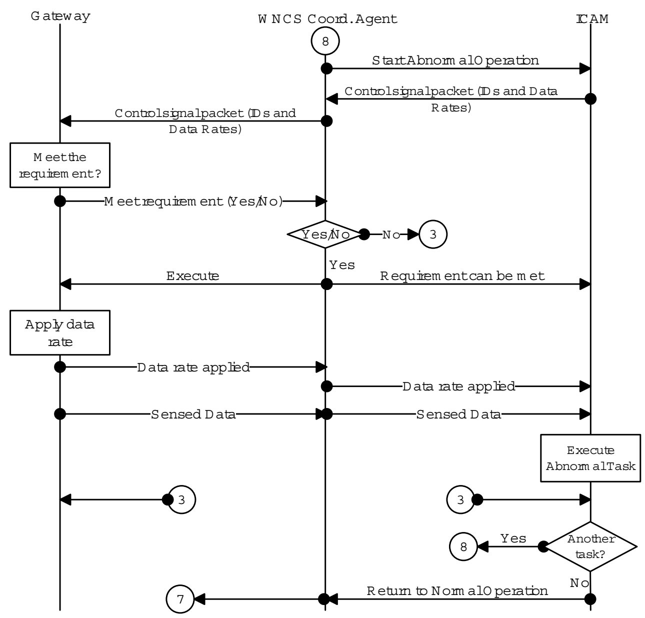

Fig. 4. WNCSCA communication scenario, Abnormal Operations Phase.

IV. Conclusion

The communication scheme described above constitutes the 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 typical WSN Gateway protocols. Great care has been taken to maintain safe and reliable operation of the WNCS. The WNCSCA has been tested and simulated extensively with the JCSTR simulator and a 5×5 mesh WSN, and good results were obtained in terms of coordinating between the ICAM Supervisor and WSN Gateway and checking the effects of WSN configurations on the performance of the closed-loop system.

The Configuration Database which was implemented and used had a major impact on checking proposed configurations in a small amount of time. The increased freedom given to the WSN 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 demonstrated that it is possible to maximize that freedom in a reliable way.

In this phase of development we have dealt with data rates and control-loop path delays, which we believe are the two most basic and important concerns. In future implementations we plan to extend the scope of the WNCSCA to handle additional WSN issues that impact control system performance, such as jitter and wireless sensor network loading effects (e.g., variation of control-loop path delay with changes in loading).

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