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Reflection: An Efficient Technique for Implementing an LTE Based Wireless Network Control System for Smart Grid and Other Applications

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Abstract—Wireless Network Control Systems (WNCSs) have been developed and deployed in many applications because of the flexibility afforded by the wireless communications medium in accommodating the control loop. In this paper, we examine a wide area WNCS using LTE as the wireless fabric. We introduce a novel concept known as “reflection” which is a subscription model that allows an LTE eNodeB to inform certain nodes in a group about low level radio signalling from certain other nodes in the group before any application data has been sent. The mean Round Trip Time (RTT) for control in an LTE based wide area WNCS which is enhanced for reflection is reduced by at least 6ms compared to a standard LTE based wide area WNCS. This is demonstrated using an OPNET simulation model that compares a reflection based architecture with a reference architecture. The technique has applications in Smart Grid control applications (such as Fault Detection and Isolation) and in other vertical industries in which WNCSs may be relevant.

Index Terms— Reflection, LTE, Wireless Network Control System (WNCS), Fault Detection and Isolation (FDI), Smart Grid.

I. INTRODUCTION

A Wireless Network Control System (WNCS) comprises nodes such as sensors, actuators and controllers connected by a wireless network for the purposes of achieving a specific control function as illustrated in Fig. 1. The advantages of using wireless as opposed to a wired connection include flexible/rapid installation of nodes and the possibility of supporting mobile nodes, while the disadvantages typically include higher latency, higher jitter and more dropped packets due to the nature of the wireless channel. Research in the field of WNCS includes both designing new control systems that can tolerate the vagaries of general purpose wireless networks and designing new wireless networks which are specifically focused on supporting control applications [1][2].

Most WNCS research has focused on IEEE 802.15.4 and its various child standards such as ZigBee which have been specifically designed for sensor and control applications [3], or else other low to medium range wireless standards such as Bluetooth [4] or Wi-Fi [5]. Very little work has been performed on the use of wide area cellular standards such as 3GPP LTE in

the context of a WNCS, and this research tends to focus only on the sensor network rather than the complete control loop [6]. This is partly because many control applications have only local scope (e.g. within a manufacturing facility) and partly because in many applications, sensors are battery powered and must be able to function seamlessly over months or even years without recharging. However, there are certainly existing control applications that possibly have regional wide area scope, particularly in the electricity, gas and oil sectors [7], and in some of these, the sensor nodes may be externally powered.

Fig. 1: Wireless Network Control System (WNCS)

In this paper, we examine a typical control application, fault detection and isolation (FDI) [8], in which the control/process loop is provided over an LTE network. The “fault” is considered to be an abstract disturbance that travels bi-directionally at a constant speed along a line on which sensors are monitoring for signs of an anomaly. This could, for example, be in a Smart Grid scenario in which the sensors are monitoring line tension or transformer temperature. However, the model is generic and we analyse different speeds of propagation for the disturbance. We first analyse how the WNCS might be implemented using a reference architecture

comprising a standard 3GPP Release 8 LTE network [9]. Following this, we introduce the concept of “reflection”, which is a proposed enhancement to LTE that allows an LTE base station (or eNodeB) to inform certain nodes in a group about low level radio signalling from certain other nodes in the group before any application data has been sent, thereby allowing control actions to be taken in a significantly shorter space of time than with the reference architecture. The notification from the eNodeB to the node(s) is performed by a new message at the Radio Resource Control (RRC) layer [10] of LTE, which we refer to as an “RRC Notification” message. Reflection can be considered to be a subscription model in which nodes subscribe either implicitly or explicitly to the low level radio activity of other nodes for a specific purpose. This is a novel concept because the network is exploiting the fact that a group of nodes are co-operating entities (as opposed to unrelated individuals) in order to offer an enhanced service to these nodes.

The reference and reflection based WNCS architectures are compared using an OPNET simulation model for our example FDI application. We illustrate several metrics, including probability of successful control, round trip time (RTT) for control and spare time when control is successful, all as a function of the speed of propagation of the disturbance. This facilitates an analysis of the realistic gains afforded by the reflection concept.

II. SYSTEM MODEL

A. Sensor Traffic Model

We consider a simple abstract model in which a set of LTE enabled dual purpose sensor/actuator nodes are equally spaced along a line. The nodes are not able to directly communicate with each other by any means. For example, this may be because the distance between adjacent nodes is too large to be served by a low range wireless ad-hoc network such as ZigBee.

The traffic model is purely event based. This is quite unusual for a wide area network such as LTE which is optimized for high rate multimedia applications. We consider a cascading alarm or fault propagation scenario in which a point along the line is selected at random, and a disturbance emanates bi-directionally from the selected point such that the disturbance takes time τ to travel between adjacent nodes or hops as illustrated in Fig. 2. When the disturbance reaches a node, that node sends an alarm to a controller (server) per the standard LTE medium access protocol.

Fig. 2: Cascading Alarm Scenario

In Fig. 2, the disturbance reaches node n first, node $n+1$ second, node $n-1$ third, node $n+2$ fourth and so on based upon the relative distances of the nodes from the origin of the disturbance. However, this is not necessarily the order in which alarms are sent to the controller over the LTE network. For example, if the nodes are in the RRC_CONNECTED state [10] (i.e. the high energy device state of LTE), each node will send a Scheduling Request (SR) message [11] to indicate to the LTE network that it needs to be scheduled for uplink data transmission. The SR is an internal low level signalling indication between a device and the eNodeB (i.e. the LTE base station), and it is not normally available to applications. The node must wait for its individual pre-assigned offset sub-frame within an SR period, T_{SR} , to send its SR [12]. Therefore the waiting time for a node to send its SR is a continuous random variable with a uniform distribution over the interval $[0, T_{SR}]$. Given this, we can imagine a situation in which the disturbance reaches node n first, but by random chance, node n has to wait a relatively long time to send its SR, whereas the disturbance reaches node $n+1$ second, but by random chance, node $n+1$ has to wait a relatively short time to send its SR, with the net effect that node $n+1$ sends its SR before node n . This is illustrated in Fig. 3.

Fig. 3: Example of Alarm Re-ordering for Nodes in the RRC_CONNECTED state ($T_{SR}=5$ sub-frames)

There is no specific application assumed by the model as it is an abstract representation in which a parameter τ can be varied to represent different disturbance propagation speeds. However, as we have noted, the model may find application in a variety of M2M wide-area monitoring and control scenarios such as in the Smart Grid, oil and gas sectors.

B. Reference Control System

We employ a reference control system which makes use of a standard LTE Release 8 access and core network as a baseline in order to fully characterise the performance gains of our reflection proposal. The reference system is illustrated in Fig. 4.

Fig. 4: Reference Control System

When the disturbance reaches a node, the node waits for its next periodic SR opportunity and then sends an SR to the eNodeB. The eNodeB schedules the node for uplink data transmission, and the node then sends its alarm to the controller (server). The controller receives alarms from various nodes as the disturbance propagates bi-directionally, and based upon certain control logic, issues unicast control commands to two nodes, one either side of the known disturbance region, in an attempt to arrest the propagation of the disturbance. We consider the control successful if both control commands are received and processed at their respective nodes before the disturbance reaches these nodes, and unsuccessful otherwise. In this reference system, all alarms and control commands are sent at the application layer over a UDP/IP/LTE stack.

The main focus of this paper is not on the control algorithms employed to manage a cascading alarm scenario; rather it is to characterize the performance gain afforded by reflection. Nevertheless, we incorporate some realistic aspects of such a control algorithm. In particular, identification of a cascading alarm situation is based upon the receipt of alarms from multiple contiguous nodes within a certain time window. In particular, the control algorithm will trigger when a run of alarms from η contiguous nodes is detected within a time window ϕ , where η and ϕ are parameters of the control algorithm. As discussed in Section II.A, there is no guarantee that the order in which alarms are received is the same order in which the disturbance reached the corresponding nodes. Therefore, each time an alarm is received, a check must be made to determine whether the reception of that alarm completes a run of alarms from η or more contiguous nodes such that all alarms were received within the preceding time window ϕ . If it does, the control algorithm sends control commands to two nodes, one either side of the run and at a distance δ from the run termination, where δ is a parameter of the control algorithm. This process is illustrated in Fig. 5 for the scenario of $\eta=3$ contiguous nodes and $\delta=2$ hops. Note how different cases can arise depending upon the order in which alarms are received from the nodes.

If the alarms contain timestamps indicating the exact time that the disturbance reached the associated node, algorithms such as double ended fault location [13] could be employed to determine the origin of the disturbance in real time and calculate which nodes should be sent control commands based upon the known or deduced speed of propagation of the disturbance. However, we do not make use of such algorithms

because timestamps are not available in the reflection scenario (at least not without significant changes to the LTE MAC layer [11]) and we wish to perform a fair comparison between the reference and reflection architectures.

(a) Simple case

(b) Alarm for node n or node $n+1$ is the last to be received

(c) Alarm for node n is the last to be received

Fig. 5: Reference Control Algorithm for $\eta=3$ Contiguous Nodes and $\delta=2$ Hops

C. "Reflection" Based Control System

A significant issue with the reference control system that incorporates a standard Release 8 LTE network is that the uplink latency is relatively high, which impacts the ability of the controller logic to respond in a timely fashion. As already noted, when a node in the high energy RRC_CONNECTED state wishes to send an alarm, it must first send a Scheduling Request (SR); this may be subject to a delay as the node must wait for its pre-assigned SR opportunity within an SR period. After the eNodeB receives the SR, it schedules the node for uplink data transmission. The scheduling may be subject to a delay in a highly loaded system. When the node receives its uplink scheduling grant, the grant applies to 4 sub-frames or 4ms in the future as illustrated in Fig. 6. As a result, the absolute minimum uplink latency is 6ms which assumes that, by chance, the SR can be sent in the very next sub-frame after the disturbance reaches the node. The typical uplink latency can be significantly higher, particularly in a highly loaded system as the eNodeB may need to delay scheduling certain nodes or when the uplink channel is poor resulting in re-transmissions.

Fig. 6: Uplink Latency Components in LTE

A different approach which significantly reduces the latency involved in making control decisions is to allow the sensor/actuator nodes to make their own decisions in a distributed manner based upon information supplied by the LTE access network about the activity of their peer nodes i.e. the nodes perform the roles of sensor, actuator and controller. This requires enhancements to the LTE access network, in particular to the eNodeB, to recognise the nodes as belonging to a group of devices that are attempting to achieve a common purpose and to send event data between members of the group. The shared data can pertain to very low level radio events such as which nodes have sent SRs, even prior to the actual data (alarms) being transmitted by these nodes. We call this concept “reflection” because the eNodeB is metaphorically reflecting event information that it gathers from individual nodes to a wider audience of nodes that belong to the same group.

Fig. 7 illustrates a distributed control system using reflection in an LTE system. In this architecture, the server does not perform a control function, but merely provides a central depository of alarms for online or offline analysis. As a disturbance reaches a node, the node sends an SR to inform the eNodeB that it wishes to send data. In the simplest case, in addition to scheduling the node for uplink transmission of data per standard procedures, an eNodeB supporting reflection may immediately inform all other nodes in the same group of this single event via a downlink signalling message. However, this is likely to cause congestion in the downlink if there are a large number of nodes in the group. A better strategy may be for the eNodeB to aggregate SR event data and only communicate it to specifically targeted nodes once a trigger condition is reached. In fact, in this respect, it is possible for the eNodeB to effectively implement the same algorithm that the controller (server) in the reference control system implements, except the algorithm searches for a run of SRs (rather than alarms) from η contiguous nodes within a time window ϕ . This is the approach we take as it facilitates a meaningful comparison between our reflection proposal and the reference system.

Fig. 7: Distributed Control System using Reflection

When the eNodeB triggers on a run of SRs, it sends a Radio Resource Control (RRC) Notification message that contains information about which nodes have sent SRs within the time window ϕ to one node either side of the identified run based

upon the distance parameter δ . RRC is an existing protocol layer in LTE [10], but the RRC Notification message is an enhancement to the standard to support reflection.

We stress that the RRC Notification message is not a control message containing commands; rather it is simply a notification of significant event activity within the group of nodes. The control decision (if any) is taken by the recipient nodes based upon the information contained in the RRC Notification messages. In fact, the concept of reflection can be considered to be a subscription model in which a group of nodes subscribe to an eNodeB service to provide low level event data pertaining to individual members of the group in order to achieve a specific objective. The subscription might be implicit and static i.e. the eNodeB knows via manual configuration which nodes belong to a group, the triggers to share data, the information to share when a trigger occurs and the set of target nodes for that data. Alternatively, the subscription details might be explicitly and dynamically set up, maintained and released via over the air messaging between nodes and the eNodeB, although this aspect is outside the scope of this paper. Another important feature of reflection is that the eNodeB does not need to understand or even be aware of the application of the subscription (in this case control of a cascading alarm); rather it simply provides the agreed information to the agreed target nodes via RRC Notification messages when specific events occur. However, in our example application where the eNodeB is reporting on runs of SRs from contiguous nodes using RRC Notification messages to specific target nodes of the group (rather than all members of the group), the eNodeB is required to understand the topology of the group in terms of the relative locations of the nodes.

Clearly, sharing data between nodes on runs of SR activity allows control decisions to be made more quickly than relying on a central controller server processing runs of application layer alarms because the SRs precede the transmission of the alarm data by several milliseconds. In fact, with reference to Fig. 6, we might expect reflection to reduce round trip times for control by at least 6ms since the control loop no longer contains the uplink grant message sent by the eNodeB (1ms), the fixed waiting time for the node to send its alarm data after receiving the uplink grant (4ms) and the return trip to/from the controller server (quantised up to 1ms which is the minimum time epoch in LTE).

However, there is an important caveat: a node sends an SR to the eNodeB whenever it needs to be scheduled for uplink data transmission. For example, when the node needs to complete a periodic location update procedure, it will first send an SR to the eNodeB. There is no direct mechanism for the eNodeB to know what the ultimate purpose of an uplink data transmission will be when it receives an SR. On the other hand, it is unlikely that the eNodeB will receive a run of SRs from contiguous nodes within a certain carefully chosen time window unless there is a cascading alarm situation in progress. Ultimately, to mitigate the possibility of a false alarm triggering an unneeded control action, a node which receives an RRC Notification message informing it of a nearby run of SRs from contiguous nodes should use not only this information,

but also its own history of local measurements to determine whether a control action should be performed.

III. SIMULATION ENVIRONMENT

Table I lists the parameters employed in the OPNET simulations to compare the reflection and reference architectures.

Table I: Simulation Parameters

Parameter	Value
Frequency Band	3GPP Band 1 [14] (1920MHz uplink / 2110MHz downlink)
Mode	FDD
Channel bandwidth	2x5MHz
Cyclic prefix type	Normal
Maximum device Tx power	1W
Maximum eNodeB Tx power	5W
Device Rx sensitivity	-110dBm
eNodeB Rx sensitivity	-123dBm
Device antenna gain	0dBi for closest 60 nodes to eNodeB 4dBi for other 20 nodes
eNodeB antenna gain	9dBi
Device height	1.5m
eNodeB height	40m
SR periodicity (T_{SR})	5ms, 10ms and 20ms
PUCCH channels	2
Channel models	Suburban fixed Erceg model with Terrain Type C [15]
Radio access network model	Single cell, 5km radius (78.5km ²)
Uplink traffic model	80 sensor/actuator nodes equally spaced along a line. Each node sends an alarm when a disturbance reaches the node.
QoS for uplink/downlink traffic	Best effort on default bearer
Uplink/downlink scheduler algorithm	Dynamic fairness
Control parameters for reflection and reference control systems	$\eta=3$ contiguous nodes $\delta=2$ hops $\phi=0.2$ seconds

IV. RESULTS

We present three metrics as a function of inter-node propagation time τ of the disturbance for the following control algorithm parameters: $\eta=3$ contiguous nodes, $\delta=2$ hops and $\phi=0.2$ seconds. All metrics are presented for both the reflection and reference architectures and for the following SR periodicity (T_{SR}) values: 5ms, 10ms and 20ms.

Fig. 8 illustrates the probability of successful control as a function of τ . As previously discussed, we consider the control successful if both control commands are received and processed at their respective nodes before the disturbance reaches these nodes, and unsuccessful otherwise. As expected, for a given T_{SR} , the probability of successful control is higher for the reflection architecture than for the reference architecture for any arbitrary value of τ because reflection allows the control decision to be taken earlier in any arbitrary scenario. As the value of T_{SR} increases from 5ms to 20ms, the mean waiting

time for an SR to be sent after a disturbance reaches a node increases, and therefore the probability of successful control is lower for any arbitrary value of τ .

Fig. 8: Probability of Successful Control Against Inter-Node Propagation Time τ for $\eta=3$ Contiguous Nodes, $\delta=2$ Hops and $\phi=0.2$ Seconds

Fig. 9 illustrates the mean round trip time (RTT) for control as a function of τ . The RTT in this context is the time interval starting when the first node becomes aware of the disturbance and ending when a (different) node receives a control command (in the case of the reference architecture) or an RRC Notification message (in the case of the reflection architecture), irrespective of whether control is successful or not. The mean RTT is a linear function of τ because as τ increases, the mean time interval for the disturbance to reach η ($\eta > 1$) contiguous nodes (and thereby trigger some action) increases proportionally. For a given value of T_{SR} , the mean RTT for the reflection architecture is approximately 6-7ms less than the mean RTT for the reference architecture for any arbitrary value of τ . This is slightly larger than the predicted value of 6ms in II.C; the difference is due to the fact that the simulation model considers re-transmissions of uplink data packets due to adverse channel conditions, but such re-transmissions only affect the control loop in the reference architecture.

Fig. 9: Mean RTT for Control Against Inter-Node Propagation Time τ for $\eta=3$ Contiguous Nodes, $\delta=2$ Hops and $\phi=0.2$ Seconds

Fig. 10 illustrates the mean spare time when control is successful as a function of τ . The spare time is defined as the time interval starting when a node receives a control command (in the case of the reference architecture) or an RRC Notification message (in the case of the reflection architecture) and ending when the disturbance reaches the same node, conditional upon the control being applied by a node before the disturbance reaches that same node. As expected, the mean spare time increases with τ as there is a larger safety margin in time to apply control once a cascading alarm event has been identified.

Fig. 10: Mean Spare Time When Control is Successful Against Inter-Node Propagation Time τ for $\eta=3$ Contiguous Nodes, $\delta=2$ Hops and $\phi=0.2$ Seconds

V. CONCLUSIONS

In this paper, we have introduced the concept of reflection, which is a subscription model that allows an LTE eNodeB to inform certain nodes in a group about low level radio signalling from certain other nodes in the group before any application data has been sent. When applied to a wide area WNCs using LTE as the wireless fabric, reflection can reduce the mean Round Trip Time (RTT) for control by at least 6ms (and possibly more in a more heavily loaded system which is currently under investigation).

There are many possible enhancements to the reflection model described in this paper. One of the most intriguing is that because the eNodeB performs both radio resource management and reflection, it can in theory modify the reflection parameters in real time in sympathy with the load, delay, jitter and/or other parameters of the system. This allows the control loop to dynamically adapt to unpredictable system behaviour in a much more granular way than is possible by simply running a control application over a generic wireless network. Another enhancement concerns the use of multicast (i.e. at the group level) rather than unicast RRC Notification messages for reflection, which is much more efficient with a large group of nodes, but which also introduces some challenges, in particular with respect to radio layer acknowledgements. Finally, we plan to generalize the cascading alarm traffic model, which is

currently a one dimensional line model, to apply to two dimensions.

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