A Critical Analysis of Open Protocol for Subsea Production Controls System Communication

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Abstract**—***Production control system communication protocols used in subsea fields are primarily proprietary to the subsea vendor. Due to the proprietary nature of this communication system, the operators encounter many challenges including obsolescence management, knowledge management and conformity assessment. This paper presents an investigation of the option of using open standard protocols for subsea production control communication system. The features, functionality and standardization of existing communication protocols used in subsea control system are analyzed and compared with open standard protocols such as DNP3 (Distributed Network Protocol) and IEC60870-5-101 and their variants used with Transmission Control Protocol/Internet Protocol (TCP/IP). The features of open standard protocols were also analyzed along with the possibility of its use in subsea production control system communication. The analysis showed that the open standard protocol DNP3 and DNP3 over TCP/IP could provide significant advantages over proprietary protocols as the specifications of DNP3 are publicly available and controlled by non-profit user group. DNP3 supports unsolicited response messages, time stamping, peer-to-peer communication and its implementation can be verified by external bodies. Furthermore, DNP3 allows the operator to integrate multiple vendors' products on a single subsea network and allows the integration of slower network with faster network without losing the data throughput.*

Keywords—Subsea; control; communication; protocols; propriety; data

I. Introduction

The first subsea control system was based on direct hydraulic control where each valve actuator had a dedicated hydraulic supply to actuate the valves. Over the years, the subsea control system has evolved from electro-hydraulic multiplex system to all electric control system. Electro-hydraulic multiplex system has been in use since the 1970s and is widely used around the world. The all electric system has been trialled during mid-2000s and will be a contender for the control system of deep water and long step out subsea fields. In both systems, subsea valves are controlled by hydraulic or electric power triggered by the electrical communication signal from Master Control Station (MCS) at the surface facility [1].

When electro-hydraulic multiplex systems were first introduced, communications were established via serial links. The communication link is used to send control signals and acquire data from subsea sensors. The communication protocols used when the multiplexed system was introduced were proprietary and were using baud rates of up to 1200bps. Though there have been developments in the telecommunications technology, the subsea data rate did not vastly improve from this slower baud rate until the introduction of fiber optics networks to subsea communication. With the introduction of TCP/IP protocols along with the developments in the fiber optic cable technology, the data rate of the subsea field communications significantly improved [2].

II. Subsea Communication System

Communication system is an integral part of the current subsea control system. Fig. 1 shows a simple block diagram of a typical subsea control communication system. It can be split into the following major sections based on its services and location.

1. Communication between MCS and Distributed Control System (DCS) - Topside

In current control system architecture, MCS and DCS are located on the fixed installation or on an onshore facility. The communication system between MCS and DCS adopted the communication technology used for processing plant control system. This varies from serial communication links (via copper wires) to the fast Ethernet (CAT6 or similar). Fiber optics is used as required based on the distance between the MCS and DCS. OPC protocol is traditionally used for the communication between MCS and DCS.

2. Communication between Hydraulic Power Unit (HPU), Electrical Power Unit (EPU), and MCS - Topside

Other topside equipment that are used for subsea control system are monitored by MCS and/or DCS. The communication link can be copper based serial links, CAT6 (or similar) Ethernet cable or Ethernet over Fiber Optic. The selection of the communication media relies on various factors including the interface available at the equipment, distance from MCS/DCS. Modbus, Profibus and other communication protocols that are used within the processing plant are used for collecting data.

3. Communication between MCS and Subsea Control Module (SCM) - Topside to Subsea

Production control system communication traditionally used communication over copper wires. Some fields use power conductors within the umbilical to super impose communication signals while the others used additional twisted pair copper wires for communications. Fiber optic cores within the umbilical are becoming popular with some

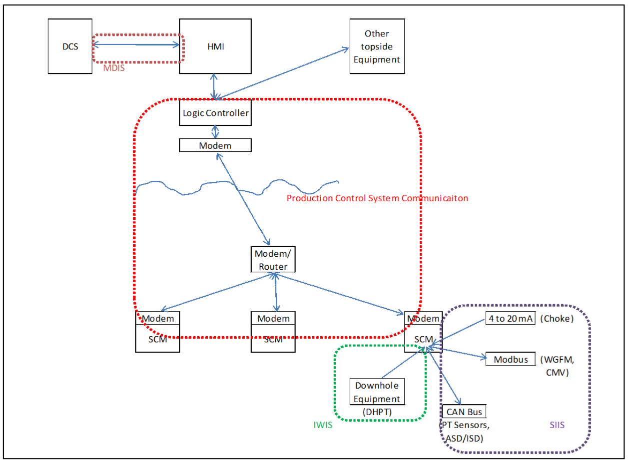

Fig. 1. Typical subsea control system communication block diagram

fields using fiber optic communication as primary communication with copper communication as backup.

4. Intelligent well completion instrument communication (Subsea)

Tubing encapsulated conductors are used to provide power and communication to the downhole instruments. Some well completions use instruments with fiber cores for monitoring.

5. Other subsea instrument communication (Subsea)

Other subsea instruments use copper cores for communications with Modbus, CANBus, 4 to 20 mA signals as the protocols.

An SCM is installed for each Christmas tree or for a group of Christmas Trees. Sensors on various locations on the subsea equipment are connected to the SCMs. A master control station on the processing facility (Topside) will poll the SCMs for information and all the data collected by SCMs is sent to MCS. Some of the sensors are installed deeper in the production tubing (down hole). These sensors have different characteristics because of the harsher conditions in which they are installed. The other sensors are installed on tactical locations so that subsea production system can be monitored. These instruments will be polled for information by SCM which in turn sends data to MCS whenever requested. Processing facility is usually monitored by a DCS. DCS will collect data from other equipment as well as from the MCS. Other equipment located on the processing facility that supports subsea control system such as HPU, power conditioning units, UPS are either connected directly to DCS or connected to MCS.

There are working groups formed to standardise the communication protocol within these sectors of subsea communication network. The only sector that does not have any sort of standardisation is the link between surface and subsea which is referred in this paper as production control system communication.

III. Communication Network Standards

The creation of network standards is one of the main drivers for the development in communication technology. It provides equipment compatibility throughout the world. Since the networks are split in smaller sectors, smaller companies concentrate on the network equipment of different sectors thus driving the technology growth. Many networking protocols were created to use different equipment and share data within a network. To understand the different protocols that are currently available, it is important to understand two main networking models, Open Systems Interconnect (OSI) and TCP/IP.

1. OSI model

OSI is a conceptual model created by International Standards Organisation (ISO). This model standardises the interaction between network systems from different manufacturers by defining seven logical layers as shown in fig. 2. The information from a layer is passed on to the subsequent layer in a structured way [3].

OSI model standardizes the rules of interaction of networked systems (from various vendors) but not the internal function of each system. When the function of a subsystem or equipment in a network is consistent with OSI model, then the subsystem or equipment can be upgraded with another manufacturer's product that performs the same functionality. For example consider a network bridge. Network bridging is performed at the data link and physical layers. A bridge from one manufacturer can be replaced with a bridge from another manufacturer as long as both manufacturers follow the interaction rules for data link and physical layers of the OSI model.

7	**Application Layer** Provides information to user	Upper Layers
6	**Presentation Layer** Coordinates representation of information	
5	**Session Layer** Starts, stops session. Maintains order	
4	**Transport Layer** Ensures the delivery of entire file or message	
3	**Network Layer** Addresses and routes data packets	Lower Layers
2	**Data Link Layer** tramits packets and collision avoidance	
1	**Physical Layer** Electrical signal and cabling	

Fig. 2. OSI Model [3]

Application layer is the highest layer in the OSI model, it provides information to the user application (Human Machine Interface (HMI) software) or the end user. Presentation layer coordinates the representation of information between different applications from the application layer. Coding and decoding of data, converting complex data structures to flat byte strings are some of the functions that fall under this layer. Session layer is responsible for maintaining an open communication channel between two network nodes during transmission. Transport is responsible for converting messages into data packets and delivering the data packets successfully. This includes retransmission of lost packets to ensure reliable delivery of messages. Network layer is responsible for addressing and routing of the data packets [4]. Data link layer is responsible for providing mechanisms to access the physical layer. This may include polling, token passing, and Carrier-Sense Multiple Access with Collision Detection (CSMA/CD). Physical layer is responsible for the physical media that connects various network nodes [5].

This seven-layered model is not applied to every network. But it is used to describe the features of the network that fits under this model and describe how they are bound together [6].

2. TCP/IP Model

While the ISO was working on the OSI model, the United States department of defence were concentrating on developing another model for faster and secure data transmission. This model has become the TCP/IP model. TCP/IP model is currently the most widely used networking model. This model has been updated by researchers from many universities from its original form to what it is now.

The TCP/IP model comprises of four layers as shown in fig. 3. Similar to OSI model, TCP/IP model does not define internal function of each layer but it standardises the interaction of networked systems.

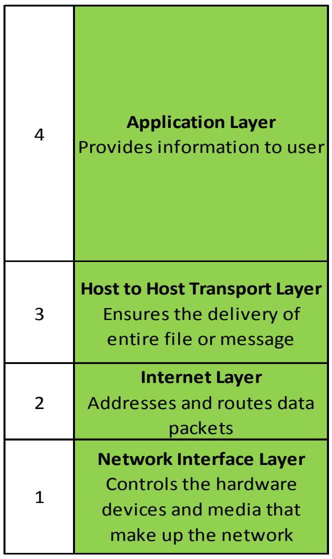

Fig. 3 TCP/IP Model [7]

The application layer defines the services that the applications which send and receive data require to communicate to the other applications in the network. HTTP, POP3, SMTP are some examples of application layer protocols. Transport layer is responsible for successful delivery of data passed on by the application layer. It includes data segmentation, delivery and error recovery functions. TCP and User Datagram Protocol (UDP) are the most common transport layer protocols in use. Internet layer is responsible for addressing and routing of the data packets passed on by the transport layer. Internet Protocol is the most common protocol used in this layer. This protocol routes data based on the IP addresses allocated to the device on the network. Network access layer is responsible for defining the access requirement of the physical media and the physical transmission of data [7].

3. Comparison of OSI Model and TCP/IP Model

Almost all of the Supervisory Control And Data Acquisition (SCADA) and data access protocols currently in use fall under one of the above two models. In some cases, some protocols combine the best functionalities of both models to suit their application.

The following figure shows how TCP/IP model is compared to the OSI model. The application layer of the TCP/IP model covers the functions defined by application, presentation and session layers of the OSI model. Transport layers map onto each other. The internet layer maps onto the network layer. The network interface layer of the TCP/IP model covers the data link layer and physical layer of the OSI model.

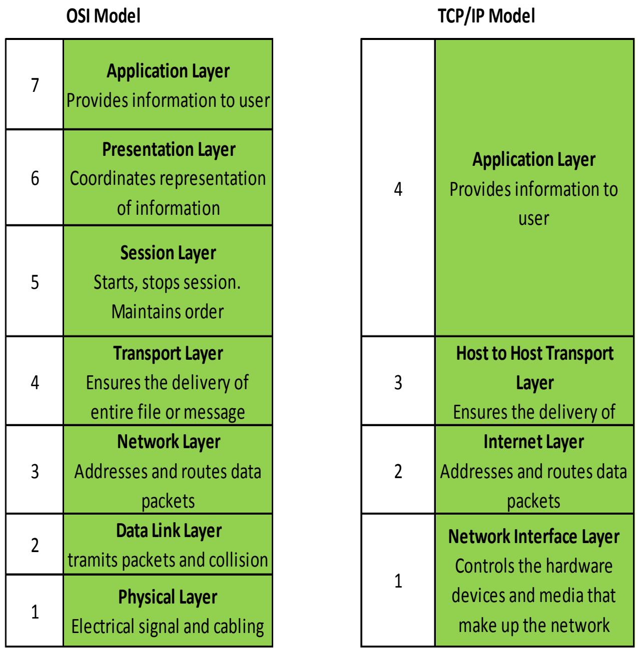

Fig. 4. Comparison of OSI Model and TCP/IP Model [3,7]

IV. OPEN STANDARD SCADA PROTOCOLS

SCADA protocols are used to control and monitor equipment that are far from central control stations. Utility industries like electric power and water industries have the need to monitor stations from long distances. With the increase of long step out subsea fields, it is important to explore the possibility of using the communication and data transfer protocols developed for other industries [8].

DNP3 and IEC60870-5 are created to specify the functional requirements of telecontrol equipment spread across wide geographical area. Though both are created primarily for electrical industry, the other industries also use these protocols for remote monitoring and control. The following sections briefly look at the basic principles and benefits of these protocols [8].

1. *DNP3*

DNP3 was first created by Westronics between 1992 and 1994 with the intention to create open standard protocol for utilities industry. Later, further development and maintenance of this protocol was handed over to the independent body DNP users group. Long distance SCADA communication is a common feature in utility industry. Since it was created to service the utilities industry, it effectively handles long distance SCADA communication. Currently more subsea fields are being developed further away from the land, and hence it can benefit from long distance communication features of DNP3 [8].

DNP3 protocol is based on the enhanced performance architecture layer model created by the IEC technical committee 57. This model is a cut down version of the OSI seven-layer model. EPA is made up of three layers as shown in fig. 5. The three layers all have similar functions to the layers in the OSI model. DNP3 has a user layer (which is above application layer) and a pseudo transport layer as an addition. The user layer offers interoperability for functions such as file transfers and clock synchronisation.

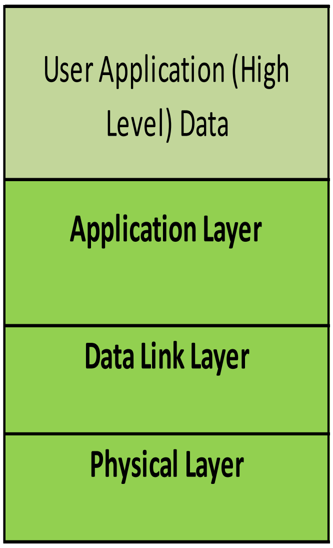

Fig. 5. DNP3 Model [8]

The application layer provides information to the user applications such as HMI or other embedded systems. The data fragment size from user application to application layer is limited to a maximum of 2048 bytes per fragment. However the number of fragments is not limited.

Pseudo transport layer handles efficient transmission of large data from the application layer. This layer breaks the data fragment from application layer into smaller chunks. The data unit has single byte transport layer header and data bytes up to 249 bytes totalling a maximum of 250 byte [9].

The data link layer provides reliable data transmission by providing flow control and error detection. Data link layer adds another 42 bytes of headers and other information to make 292 bytes long data fragment.

Data link header frames includes 2-byte long source and destination addresses. This allows 65536 addresses. Data link layer can also implement additional security by requesting confirmation of receipt for every frame that is transmitted.

DNP3 has some additional features that the other SCADA protocols do not have. DNP3 protocol can request and respond with multiple data types within a single message. Message segments can be split into multiple frames at pseudo transport layer level which helps for error detection and error recovery. It also supports unsolicited messages or message response without requests, priority allocation for each data point, response for changed data, data quality information, event time stamp and many others.

2. IEC60870-5-101

IEC 60870 is the standard created by IEC for telecontrol equipment and systems. Part 5 of this standard details the transmission protocols for the telecontrol. Part 5 has five sections. They are 5-1: Transmission Protocol, 5-2: Link Transmission Procedures, 5-3: Structure of Application Data, 5-4: Definition of Application Information Elements, 5-5: Basic Application Functions. Part 5 also has some additional companion standards. They are 5-101: Basic Telecontrol Tasks, 5-102: Transmission of Integrated Totals, 5-103: Protection Equipment, and 5-104: Network Access. IEC 60870-5-101 defines the basic telecontrol tasks over serial network and IEC 60870-5-104 defines the telecontrol tasks over TCP/IP network [8].

Like DNP3, IEC60870-5-101 also uses the enhanced performance architecture created by ISO. This protocol has a user layer but does not have any of the pseudo transport layer functions that DNP3 has. IEC60870-5-101 has a set of data objects that can be used for general SCADA applications and another set specifically for electrical system applications. Each data type has unique identification number. Only one type of data can be included in any application data unit.

3. IEC60870-5-104

Like DNP3, the International Electrotechnical Commission (IEC) realised the importance of carrying data over TCP/IP network. This has prompted IEC to create specification for carrying IEC60870-5 data packets over TCP/IP. This is recognised as IEC60870-5-104.

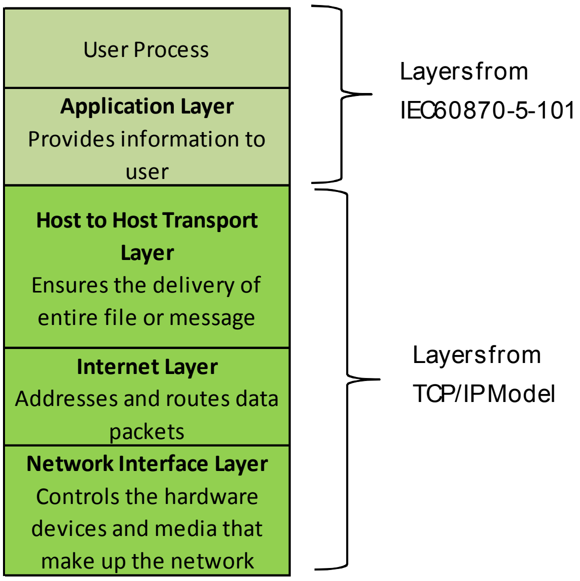

Fig. 6. IEC60870-5-104 Model [8]

Unlike DNP3, IEC60870-5-104 only keeps the application layer from IEC60870-5-101. All the other layers (data link, physical layers) were replaced by the lower layers other than application layer of TCP/IP model (see fig. 6) [8]

V. Upgrading Existing Subsea Production Control System Protocol

Many of the existing fields use serial protocol over power conductors or copper communication lines. The newer fields have fiber optic communications as the communication media and TCP/IP as the carrier protocol (Transport layer and internet layer). The proprietary serial protocol is encapsulated within TCP/IP packets.

Operators do not like to upgrade existing subsea communication architecture unless there is major breakdown in the system or field life extension is required. This is mainly due to the cost involved in changing out the system as well as the loss of production due to the field unavailability during the upgrade. Any upgrades to an existing field will involve a lot of planning and testing prior to implementation to enable online cutovers. This may require interim configurations and alternative communications path (backup communication) or to reduce the down time. When there is an opportunity for an expansion within proximity of an existing field, there are two options available for the operator. One is to use the existing architecture, products and spares for the new wells. This will utilize the old technology available with reduced data rate. The other is to upgrade the existing subsea control system or install a new subsea control system. The decision will heavily rely on the cost benefit analysis of all the options available.

Some of the proposed ways to upgrade a subsea production control system is presented as follows;

1. *Replace all controllers in the subsea field*

In this method, all subsea controllers and the MCS in the subsea production control system network will be upgraded with the new controllers. The new subsea controllers shall support connectivity of these existing instruments and shall be able to accommodate the logic functionality of the previous controllers. This method is effective for smaller fields where the cost benefit analysis does not have much difference compared to the other options detailed below. A communication signal analysis is required to identify any issues with the new communication protocol upgrade. Fig. 6, fig. 7 and fig. 8 show the pre and post upgrade status of the various subsea communication architectures for single channel.

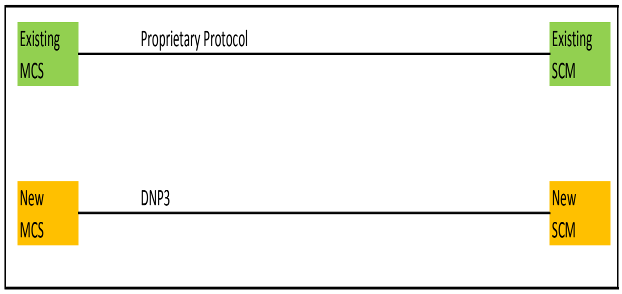

Fig. 6. One to one network architecture

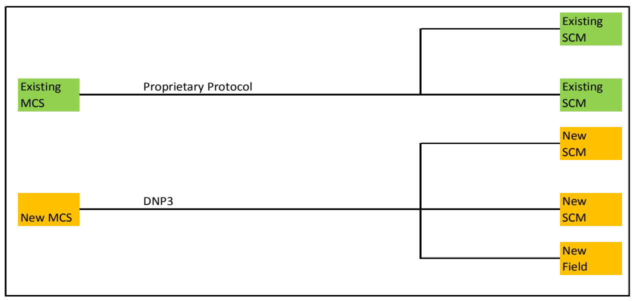

Fig. 7. Star network architecture

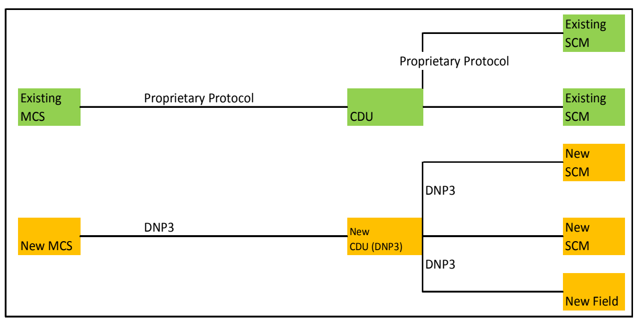

Fig. 8. Hybrid network architecture

2. Install protocol at each controllers in the subsea field

In this method, the MCS will be upgraded with new controllers and communication protocol. A protocol converter will be installed at each subsea controller. The protocol converter will convert the previous communication protocol to the new communication protocol.

In this approach, any communication distribution modules that behave like router will need to be upgraded to support the routing of new protocol. This method relies on the ability in implementing and validating the protocol converters. Fig. 8, fig. 10 and fig. 11 show the pre and post upgrade status of the communication network of various subsea architecture.

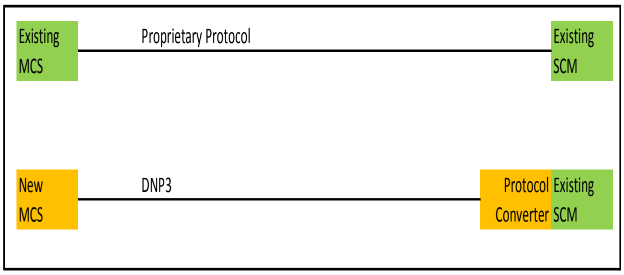

Fig. 9. One to one network architecture

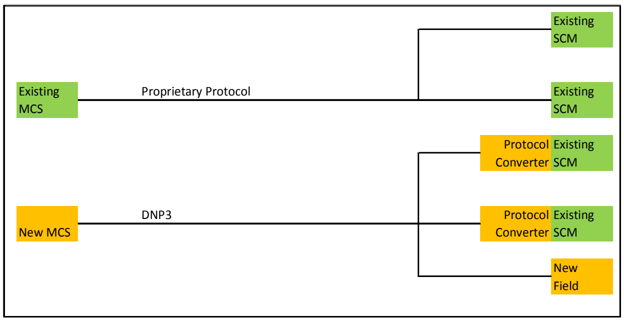

Fig. 10. Star network architecture

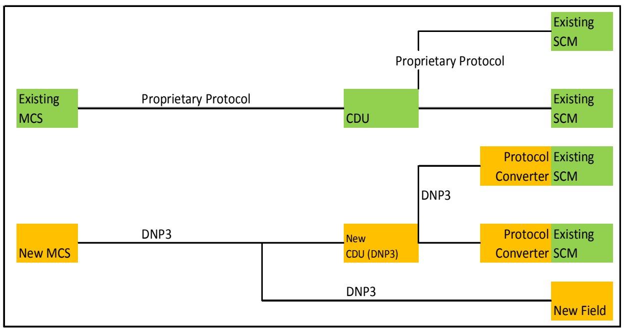

Fig. 11. Hybrid network architecture

3. Upgrade existing communication architecture

In this method, the sections of the MCS that relates to old communication protocol is moved to the farther most point in the field. This will allow the operator to use the existing subsea system (such as umbilical, umbilical termination assembly etc.) for the new system with faster data rate while keeping the old system integrated with the new system. This option will require a new hardware controller which manages the interface between the old protocol and the new protocol.

The new interface controller will allow the integration of the existing field with proprietary communication protocol with new field with open communication protocol. Fig. 12, fig. 13 and fig. 14 show common subsea production control system communication architecture that are currently in use and how the interface controller will be utilized for the protocol upgrade.

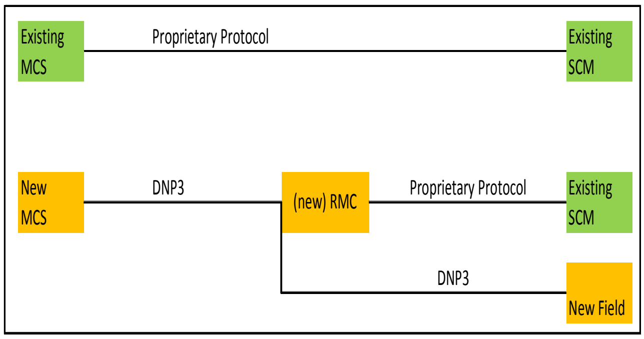

Fig. 12. One to one network architecture

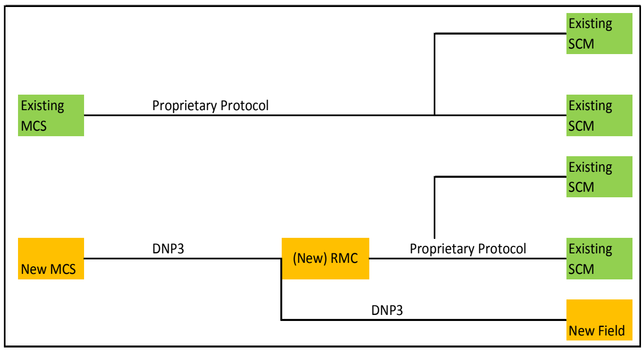

Fig. 13. Star network architecture

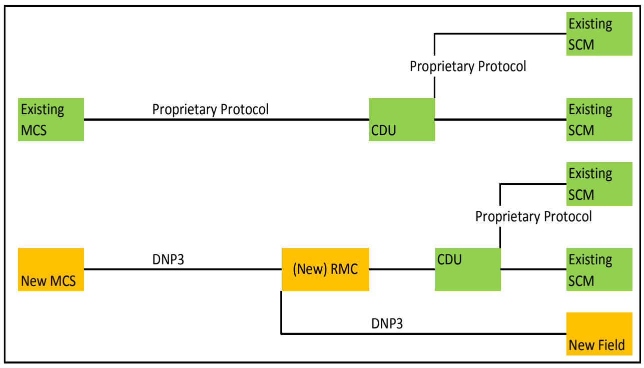

Fig. 14. Hybrid network architecture

VI. CONCLUSION

With the development of the semiconductor industry, communication technology has been rapid progress. General purpose controllers are cheap and short lived. Subsea fields require controllers with high reliability and availability due to the cost involved in changing out controllers. Subsea control system vendors use controllers with proprietary protocol to increase the reliability and availability of the communication and control system of subsea fields. Many projects and joint venture partnerships have been undertaken to standardise the communication protocols between Subsea controllers and Downhole instruments, subsea control module and subsea instruments, MCS and DCS (both on topside). But production control communication protocols have remained proprietary.

Subsea industry is somewhat different to other industries because of the lack of access to controllers and the cost involved in performing an intervention. But there is an opportunity to apply the lessons learnt from the transformation the other industries have taken. Utilities industries initially used proprietary protocols, but switched to open protocols (DNP3, IEC60870-5). Considering the benefits of using DNP3 (over serial and over TCP/IP) protocol over proprietary protocols, it is important that production control communication protocols are to be standardized to DNP3 protocol.

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