Synchronisation Challenges within Future Smart Grid Infrastructure

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***Abstract*— Synchronisation of computer systems is a challenging task when the systems communicate across a dynamic and variable latency network but becomes especially challenging when the network contains wireless communication links. The success of the evolving smart grid project will depend hugely on Information and Communication Technologies to revolutionise the traditional power grid and will place various demands on current synchronisation techniques. Utilisation of wireless communication systems within the smart grid infrastructure seems inevitable, thus, if the project is to reach its full potential then some of the shortfalls of current synchronisation techniques over wireless must be remedied. This paper reviews the vital role of synchronisation within current and future smart grid infrastructures and outlines some proposals to remedy the shortfalls of current time synchronisation techniques. In particular, we focus on improving the implementation of the Network Time Protocol over 802.11 networks along with an optimisation technique to reduce the energy usage of a common Wireless Sensor Network synchronisation protocol.**

Keywords-802.11, NTP, PTP, Synchronisation, WSN.

I. INTRODUCTION

The current grid is a real-time system whereby generation must always match demand. In any real-time system, time is a critical factor and when the system is distributed, synchronisation of its various elements is essential. Current grid infrastructures employ synchronisation techniques to permit such functions as fault detection, protection testing, load balancing, scheduling and analysis. Supervisory Control And Data Acquisition (SCADA) [1] systems play a very significant role in grid operation and through the use of synchronised time also permit logging of data which, can prove useful in determining the events leading up to and during disturbance events. In distributed power generation, geographically distributed generators supply power to the grid and synchroscopes ensure that they do so safely by synchronising frequency and phase.

In recent years, more advanced ICT (Information and Communication Technologies) systems based on synchronisation techniques have evolved. These include fault detection systems such as the Fault Location Acquisition Reporter (FLAR) [2] system developed by the Bonneville Power Administration (BPA) in the US and PMUs (Phasor Measurement Units) [2] that utilise precisely synchronised phasor measurements to produce an instantaneous picture of the entire state of the grid in real time.

Looking to the future and the evolving Smart-Grid/Smart-Networks project, the role that time, timing and phase synchronisation will play will greatly expand. Smart grid will rely on advanced ICT technologies to revolutionise the traditional electricity grid. Smart grid will by definition significantly increase the complexity of the current grid's static design by transforming it into a much more dynamic network where the distinction between producer and consumer will often be blurred. The composite elements of this complex system will place significant demands on current synchronisation technologies in order to meet its full potential.

The remainder of this paper is structured as follows. Section II outlines the role of synchronisation techniques within the traditional grid. Section III highlights some of the possible synchronisation requirements of future smart grid systems. Section IV details some of the synchronisation techniques employed in current ICT systems and highlights the challenges of deploying these techniques over wireless communication links. Section V outlines some solutions to meet these challenges. Section VI concludes the paper.

II. ROLE OF SYNCHRONISATION IN CURRENT GRID INFRSTRUCTURE

Current grids operate using a demand-response scheme whereby electrical energy is generated in response to real-time demand. SCADA systems play a key role, performing four distinct functions, namely, data acquisition, data communication, data presentation and control. In relation to data logging, data collected using a SCADA system must be time stamped in order to determine the correct sequence of events. This is performed by Remote Telemetry Units (RTU) which, timestamp sensor data, typically to within a few milliseconds of global time.

A. Advanced Grid Synchronisation Topics

In recent years, the role of time synchronisation within grid infrastructures has evolved. One particular advanced application of synchronisation is transmission cable fault detection. In the case of a cable fault, manual inspection can be impractical, time consuming and costly. Some impedance based automatic fault location systems are prone to error. When a power cable is damaged an electromagnetic noise burst is propagated out which, can be detected and timestamped by fault detection units at substations on each end of the cable. Subsequent analysis of the reception times can deduce the position of the fault based on signal Time of Arrival (TOA). This system is only effective if the devices on each end are synchronised to within a microsecond or better. Synchronisation of this granularity allows the location of the fault to be determined to within 300 meters. The Fault Location Acquisition Reporter (FLAR) developed by BPA in US is

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based on this scheme. The FLAR system has fault detection units located at numerous substations, each synchronised using GPS.

Another example is Phasor Measurement Unit (PMU) technology. A PMU is a device which, provides phasor information associated with a particular point on the power grid. This information describes the magnitude and phase angle of a sinusoidal waveform. If a number of PMUs are placed at various locations within the power grid and synchronised to within a microsecond of each other they can provide precise real-time information regarding the state of the grid. This proves invaluable for monitoring grid activity. PMUs employed in this manner are referred to as synchrophasors and form an integral part of a fully functional phasor network. A complete phasor network consists of dispersed PMUs together with Phasor Data Concentrators (PDC) to aggregate PMU data and a SCADA system to monitor the accumulated data. In a typical deployment PMUs are synchronised through the use of integrated GPS receivers. Each PMU sample is time stamped and transmitted to a PDU using a standard protocol. The PDU correlates samples from multiple PMUs based on time stamps and forms a measurement set for that particular segment of the grid. The PDU then provides a direct output to a SCADA system which, provides a real-time visualisation of that grid segment.

Finally, many line protection systems are based on precisely synchronised data for correct operation. Loss of synch can cause inadvertent (false positive, false negative) operation. For example, a utility might incorporate dedicated fiber links between grid sensing devices and a central aggregator. The propagation time of data via these links would be constant and known allowing data to be time stamped solely at the aggregator. If these links were to be replaced by leased lines incorporating deferent communication technologies and subject to varying traffic loads then time stamping solely at the aggregator would most likely be problematic.

III. Smart Grid

The smart grid project aims to revolutionise the current grid infrastructure in order to reduce inefficient energy consumption, to facilitate the move towards renewable energy, and to better utilise the grid's capacity so as to accommodate growing electricity demand. A key driver for this will be through integration of ICT into the electricity grid, from generators through transmission right down to consumers. The current grid is based largely on one-directional power flows in a demand-response scheme. The system is designed to handle peak demand by adding additional and less efficient "peaking" capacity, thus adding to the overall cost. A smart grid system will use a variety of technologies to monitor and better control consumer demand, possibly incentivised through real-time pricing structures. A core objective is to level the current peak demand curve thus reducing total costs and ensuring that additional grid capacity is used to its full potential. The extent to which, consumers will be motivated to control/minimise energy usage either due to environmental concerns or (more likely) economic cost remains to be seen and will dictate the success or otherwise of demand side management (DSM) strategies.

It must of course be borne in mind that the smart grid is not an end in itself, but a means to an end, and if there are other approaches which, meet the goals of increased fuel security (from local renewable resources) and reduced emissions (from decreased usage of fossil fuels) these should also be considered e.g., reconductoring transmission lines in High Temperature Low Sag (HTLS) Conductor to provide an extra 50% capacity. Additionally, smart grid can only operate where there is an existing Grid, and where this Grid has the capacity or "headroom" to operate as flexibly as smart grid system dynamics require.

As such, a smart grid system may facilitate generation from independent suppliers utilising different generation techniques, renewable or otherwise. These might include Combined Heat and Power (CHP), solar/wind/ocean energy, micro-generation as well as more futuristic sources such as Vehicle to Grid (V2G). Smart Metering at each consumer premises has a key role to play in this.

Technologies incorporated within the core of the grid will thus include HTLS conductors for efficient electricity transmission, storage units to house generated surplus energy and advanced PMU-based power flow monitoring for real-time grid activity monitoring. Within such a smart grid system the scale and complexity of SCADA systems will increase in orders of magnitude from current systems. Such SCADA systems may operate at a macro grid level or localised within micro-grids. Already, we have seen large strides in Energy Management Systems (EMSs) for end customers that seek to minimise/manage energy use. Currently, these communicate internally via a Home Area Network (HAN) with a multiplicity of devices to manage demand. In future, these will also be integrated within smart grid as they have an important role to play, leading to a merging of smart building, smart metering within the smart grid umbrella. We briefly describe both smart metering and smart buildings in later sections.

The evolution of smart grid systems will also extend to the transport sector. For many reasons, electric vehicles will be a key driver of DSM at customer level by incentivising charging in valley periods. Looking further to the future, vehicle-to-grid (V2G) systems may materialise allowing vehicles to take on the role of both an energy consumer and supplier within the grid.

While a wide variety of technologies will be essential to make a smart grid system a reality, one fundamental aspect will be the synchronisation technologies employed to glue the system together. A smart grid system will effectively be a large real-time distributed system and as such time and frequency will play a key role in its correct operation. Synchronisation of various elements of the system will be vital for effective monitoring and control of energy flow from suppliers to consumers, see Fig. 1.

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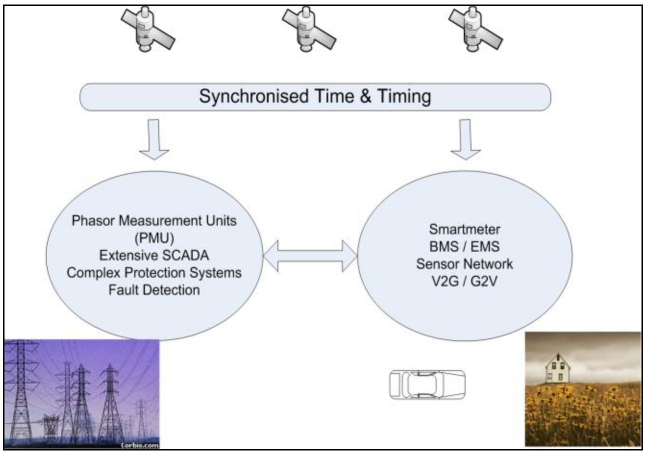

Figure 1- Synchronisation of Grid Elements

A. Smart Metering

An effective smart grid system can only be realised by means of precise real-time monitoring and control of power usage down to the end-consumer. Real-time monitoring of power usage permits accurate analysis of daily demand and allows for construction of an efficient energy plan based on real-time pricing. Recent years have seen the wide scale deployment of so-called smart meter trials in numerous countries across the globe. In contrast to traditional meters a smart meter provides a more comprehensive report of power consumption in addition to bi-directional communication capabilities. In a future scenario, smart meters could provide real-time data to a Home Area Network (HAN) that manages an internal Energy Management System; the HAN in turn will communicate externally with the smart grid. As such, meters must be synchronised to Universal Coordinate Time (UTC). HAN communication methods that have been used include Power Line Communication (PLC), Wired LAN, Wi-Fi and licensed radio networks. Undoubtedly, smart metering will play a key role in the development of future smart grid. One might envisage a multiplicity of smart meters within a commercial or industrial building each monitoring the activity of a power intensive system, for instance, a heating or air conditioning system. Each of these smart meters would be synchronised to a global time reference for use by the consumer’s EMS. Analysis by the EMS would provide a means to construct a schedule to better optimise, from a cost perspective, the operation of these systems. Such a system would also permit DSM incentivised schemes including automatic load shedding in low frequency situations brought about by sudden loss of generation. Such notifications to the HAN will likely use both broadcasting and unicasting techniques, the former to reach multiple aggregated consumers where low priority loads could be removed at short notice, and the latter to manage larger individual loads.

A more elaborate scheme within a building might integrate networks of sensing devices to provide in-depth analysis of individual systems. For instance, sensing devices capable of measuring temperature, airflows could be dispersed around a building and networked together to form a Wireless Sensor Network (WSN). Data collected from sensors within a WSN needs to be time stamped effectively. Thus, use of WSN synchronisation techniques such as the Reference Broadcast Synchronization (RBS) algorithm [3] or the Flooding Time Synchronization Protocol (FTSP) [4] will be essential though the extent of synchronisation required is application dependent.

B. Smart Buildings

As described, both smart building and smart metering technologies are essential in the evolution of smart grid. Smart building is a term used to describe a building automation system with advanced automatic systems for controlling heating, cooling, lighting, security and various other functions. A smart building home controller may take the form of a PC with the required hardware and software to communicate with and monitor the systems. Communication between different devices might also be facilitated through emerging standards such as BACnet [5] or KNX [6]. As described, HAN communication between a home controller and various automated systems might be performed using a Power Line Communication protocol or some wireless protocol such as ZigBee or Wi-Fi. Coordination of the automatic systems within a smart building will typically be performed by defining various operating modes via the home controller. An operating mode may define the lighting, heating, air-conditioning and security requirements for a particular time of the day which, is subsequently activated automatically at that time by the synchronised home controller. The use of smart meters together with building automation systems would provide a means to better define operating modes that would meet an individual’s desired demand profile.

C. Electric Vehicles

Electric vehicles (EVs) have a key role to play in smart grid by facilitating national strategies for reducing reliance on fossil fuel energy and moving to renewable electricity based on wind/ocean/biomass etc. Besides the environmental benefits, the use of indigenous sources of energy will eliminate external dependence, however, it will require a large initial investment and the benefits may not be observed for many years. Currently the main disadvantages of EVs are the low energy density and lengthy recharging time of their batteries, issues which, are likely to be remedied in future years. While it is largely agreed that EVs have a key strategic role to play in reducing fossil fuel dependency and fostering DSM (through off peak charging tariffs), it also appears possible that they may also take on the role of suppliers through vehicle-to-grid (V2G) technologies. Similar to the situation described above with smartmetering/smartbuildings, a V2G system will communicate via HAN to the grid and would allow EVs to provide electricity to the grid during critical events or during peak hours, thus helping to reduce need for traditional spinning reserve and inefficient peaking plant. A V2G system could also act as the main supplier to a residence in the event of an outage.. Ireland has a very ambitious target for electric vehicle penetration with a strategy to achieve 10% all-electric vehicles by 2020 with 3,500 charge points by 2011 underway [7].

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IV. SYNCHRONISATION OVER ICT

The future scenario of a smart grid facilitated through smart metering and smart buildings will place huge demands on the supporting ICT infrastructure. As detailed, the current scale of SCADA will increase in orders of magnitude and such SCADA, operating at macro or micro scale will be IP based. For example, the SCADA system operated by ESB Networks, the Irish Distribution System Operator for the whole country currently communicates with < 1000 Medium/Low voltage sub stations connected largely through dedicated radio and roughly 1000 pole mounted devices with third part GPRS connectivity. Contrast this with possible future smart grid deployment that will see at a minimum each consumer smart meter and HAN connected. In addition to this, it is likely as outlined that via a the consumer's HAN, multiple devices such as secondary smart meters, vehicles, and various appliances will be connected, To facilitate this scenario, each node will have its own IP address to facilitate management within the HAN and also outside as they interact with smart grid. As such, the scale of the required infrastructure for a small country with just over 1m homes represents a huge step in SCADA scope. Realistically, a hierarchical network of SCADA systems will be deployed to distinguish between critical infrastructure i.e., substations and less critical. For example, in an Irish context, there are approximately 12,000 MV/LV substations of 200kVA and over. Moving to IP will ease some complexity but has already raised serious security and privacy concerns. Within the high, medium and low voltage grid, where power flows will be much more dynamic, the architecture of monitoring, control and protection systems will all have to be redesigned to meet the changing requirements.

Synchronisation of various elements of a smart grid system will be vital for effective monitoring and control of energy flow from suppliers to consumers. Smart grid will thus most likely incorporate the synchronisation techniques utilised by current ICT systems. The motivation for sync can be attributed to the imperfections in current computer system clocks which, typically utilise inexpensive quartz crystals as their frequency standard. While systems such as Oven Crystals and Global Navigation Satellite Systems (GNSS) (GPS, Glonass and Galileo) act as a very reliable and accurate source of time, they are not a practical or cost effective time sync solution in many scenarios As such the use of a software based synchronisation protocol is favored.

A. NTP & PTP

At present NTP (Network Time protocol) [8] and PTP (Precision Time protocol) [9] are the de-facto synchronisation protocols utilised over wired networks. NTP is designed for dynamic and variable latency packet switched wide area networks and can attain low-millisecond accuracies if well managed. PTP can attain microsecond accuracies over LANs, thus, meeting the precision requirements of applications that NTP cannot, but at the cost of requiring a tightly managed network and specialised time stamping hardware.

B. Synchronisation Errors

NTP and PTP use pair-wise synchronisation to synchronise the clocks of computer systems whereby a host wishing to be synchronised sends a time request to a reference node and records the transmission time t1. The reference node replies with the reception time of the request message and transmission time of the reply message, t2 and t3 respectively. The host node records the reception time of the reply message t4 and uses the four timestamps to calculate the propagation time and, thus, determine its clock offset from the reference. (1).

$$\theta = \frac{t2+t3-t1-t4}{2} \qquad (1)$$

This technique operates on the assumption that the each-way message delays between a sender and receiver are symmetric. If this is not the case, which, in reality is often true, then the calculation of a clock's offset from its reference will be inaccurate. The different sources of synchronisation errors can be attributed to the different components of a synchronisation message's latency. These components can be categorised as the send time, access time, propagation time and receive time. The send time represents the time taken for a host to construct a synchronisation message and transfer it to the network interface. The access time corresponds to the delay incurred by the network interface while waiting to gain access to the communication medium. The propagation time is simply the time taken for the message to travel to the receiver once it has left the sender while the receive time represents the time taken for the receiver's network interface to receive the message from the communication medium, decode it and notify the host application that it has arrived. It is important to note that, with pair-wise synchronisation, the magnitude of a message's delay is not the factor which, results in a clock error but rather the difference between the delays of a request message and a response message.

NTP and PTP use different techniques to mitigate the effects of non-deterministic delays on time estimation. NTP references multiple time sources and utilises a suite of statistical algorithms to deduce the most probable clock offset. Conversely, PTP takes advantage of the fact that its operating environment is managed and employs PTP-aware internetwork nodes and hardware time stamping to increase precision. While these techniques prove very effective it is important to note that both NTP and PTP were designed to operate within the wired domain, and as such, wireless links pose greater challenges.

C. Wireless Issues

A wireless network utilizes a shared medium that must be allocated to individual nodes in a protocol-dependent fashion. Depending on the technique used and the traffic load at a particular time, transmission of packets between two particular nodes may be subject to large contention delays. The most accepted and widely implemented set of standards for wireless communication over LANs is defined by IEEE 802.11. The basic 802.11 specification defines both the physical and data link layers for communication across a wireless network. Access to the wireless medium as defined by the 802.11 MAC layer is controlled by the distributed coordination function (DCF) which, controls access by using a CSMA/CA (carrier sense multiple access with collision avoidance) mechanism. It operates by first checking that the medium is clear using carrier sensing functions and if so begins transmission. If the medium is in use the station backs off for a random time interval to avoid a collision. In the case of an 802.11 network, all nodes including the access point conform to the same access rules. Since the access point (AP) carries out extra work, an NTP host operating over an 802.11 network with competing nodes can experience significant asymmetric round-trip delays and, thus, accumulate significant clock errors. In relation to a smart building with time sensitive devices running NTP implementations and communicating via the building's Wi-Fi LAN this would prove problematic.

D. Wireless Sensor Networks

As mentioned in section III, WSNs will most likely form a significant segment of smart grid, particularly at the consumer side. The greatest issue concerning WSNs is their limited energy supply. Thus, techniques to ensure optimal use of power consuming sensor components by synchronization algorithms will be required.

V. CONTRIBUTION

To summarise previous sections, future smart grid systems will be highly complex and dynamic and will require a comprehensive ICT support infrastructure for stringent monitoring and control of demand in real-time. These systems will require various degrees of synchronisation from generation down to the consumer premises. Within the latter, communication between nodes may be over wired or wireless networks. Wi-Fi is currently the most popular form of wireless communication due to ease of operation and installation. However, as described, contention delays can severely decrease the accuracies achievable by current time protocols and as such solutions must be found. In addition to this, the use of WSNs within smart grid systems will require that energy saving techniques are incorporated into WSN synchronization protocols to prolong battery life whilst maintaining adequate synchronisation levels.

A. Synchronisation over 802.11

One solution to asymmetry being implemented by the authors entails the use of 802.11 acknowledgement frames (ACKs) and special probe frames to deduce and eliminate the non-deterministic medium access times at the host and access point. Unlike many data link layer protocols, 802.11 incorporates positive acknowledgements. All transmitted frames must be acknowledged by the receiving party via an acknowledgement frame or the transmission is considered a failure. The transmission of data and reception of an acknowledgement is an atomic operation and must be completed fully or not at all.

As illustrated in Fig. 2, if the sender of a time message records the reception time of its corresponding ACK frame that sender could largely eliminate the non-deterministic send time, and more importantly, the medium access time of that message. The result would be the elimination of the effects of traffic contention and sender delays in the upload direction of the time message. While this method would be beneficial to some degree it would not address the larger issue of non-deterministic delays in the download direction. Larger download delays can be attributed to the fact that users in general download more data than they upload and more importantly, an access point must compete with all other wireless nodes equally. To estimate download delays the sender could send a special probe request frame to the access point that would initiate a corresponding response frame. The reception times of the request frame's acknowledgement and the response frame could then be used to estimate the send and access delays at the AP at that point in time, thus, reducing asymmetry errors.

Another possible solution being explored is improving synchronisation accuracy by real-time analysis of network related data. Analysis of past data can help to quickly identify network trends and make predictions about the state of the network. Both statistical techniques and more elaborate methods such as artificial neural networks are being investigated. A statistical approach might involve analysing network related data and forming a probability model to infer the most probable behavior of the network at a particular point in time. In addition, analysis of the correlation between a time packet's round trip delay and the corresponding estimated offset could be used to identify and correct for probable asymmetric delays. An artificial neural network could provide an even more effective solution by recognising patterns in the network and using this to improve NTP performance.

At an abstracted level, both approaches can be viewed as a module that can be linked to some synchronisation protocol and used to mitigate the asymmetric effects of wireless contention. For instance, an intermediate MAC to NTP interface module could provide one or both of the above techniques depending on the condition of the wireless network. (Fig. 3).

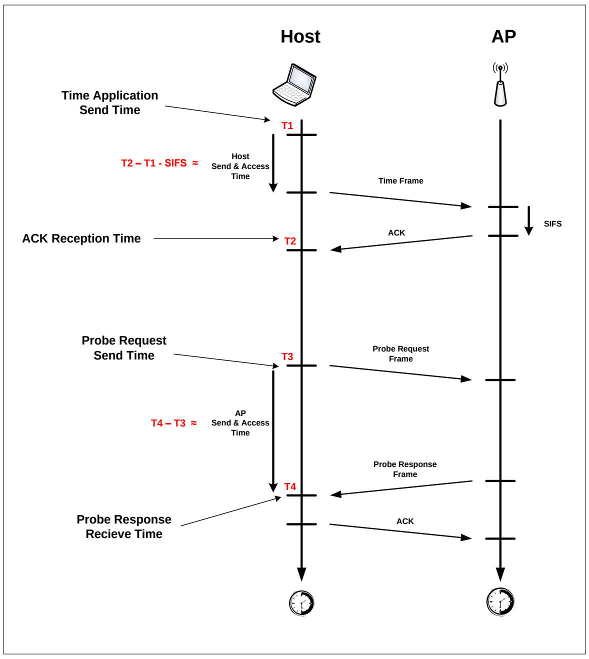

Figure 2. Determination of send and MAC delays

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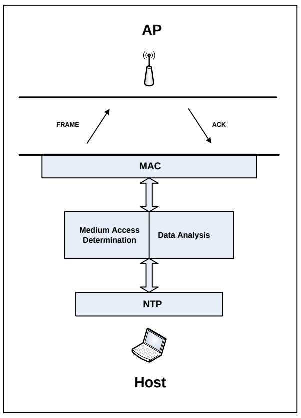

Figure 3. MAC to NTP interface module

B. *Energy Conservation in WSN*

At present FTSP is the de facto synchronisation protocol used in WSNs. To retain the precision requirements of a WSN application, FTSP nodes must broadcast messages at a predetermined periodic interval, the value of which, is influenced by the nodes operating environment and to a lesser extent their clock characteristics. These periodic transmissions allow nodes to determine their clock skew relative to an elected root node. In most cases this transmission interval is not optimal resulting in needless radio transmissions and, thus, energy wastage.

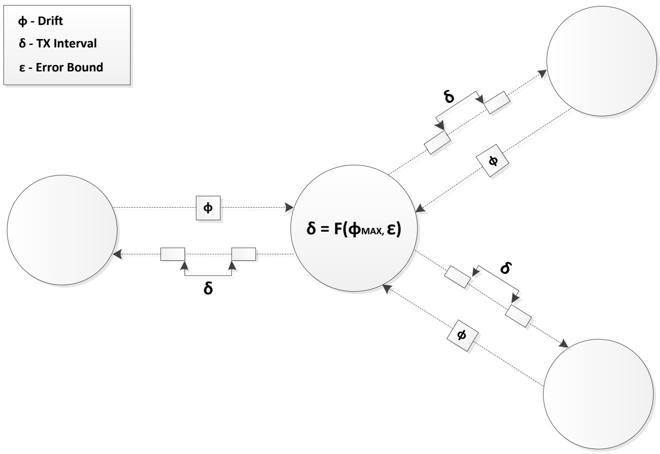

Figure 4. Dynamic FTSP

A solution the authors are currently implementing is to have an FTSP node alter its transmission interval based on the overall precision requirements of the WSN application and the rate of change of skew of neighboring nodes. A node's transmission interval would therefore be dictated by its most unstable neighboring node. This technique will result in a significant reduction in transmissions particularly in a variable operating environment (Fig. 4) and allow an administrator to customise the synch level for the application domain.

VI. Conclusions

This paper has explored the vital role that synchronisation currently plays in electrical grids and has highlighted the importance of synchronisation in the evolving smart grid project. It is certain that future smart grid systems will rely heavily on current ICT technologies and synchronisation techniques. This paper has briefly outlined two research projects to improve synchronisation performance over wireless networks. The first focuses on NTP performance over Wifi whereas the second has developed a novel extension to the FTSP protocol for sensor networks that will deliver quality synchronization at reduced energy cost.

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