Wireless Communication For A Modular Heliostat Field

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***Abstract*—The global demand for affordable renewable energy has driven Stellenbosch University's Solar Thermal Energy Research Group, STERG, to design and construct a modular heliostat field for a central receiver concentrating solar thermal (CST) plant. The heliostat field requires a robust wireless communication network with sufficient range, bandwidth and low latencies to enable a high level of control over each heliostat. Currently several wireless communication technologies are available on the market such as LoRa and LoRaWAN, NB-IoT, ZigBee, Bluetooth low energy (BLE) and Wi-Fi and its variants. In this article these different wireless communication standards are investigated within the scope of a modular heliostat field. The advantages and disadvantages of each is discussed with regards to range, bandwidth, energy consumption, ease of implementation and latencies. Furthermore, different architectural designs for wireless networks are analysed. The Wi-Fi 6 standard (IEEE 802.11ax) operating in a star network topology is proposed for the modular heliostat field. This technology is able to operate with sufficient range, throughput and minimal latencies in a dense network such as the proposed CST plant. This work is part of the H2020 PREMA project, aiming to advance novel energy systems in the drying and pre-heating of furnace materials.**

***Index Terms*—CSP, CST, wireless, communication**

I. Introduction

Worldwide there is an urgency to accelerate the rate at which renewable and sustainable energy generation is implemented. This is due to the finite amount of fossil fuels being exhausted at a rapid rate and the unmistakeable environmental impact thereof. In 2014 the South African CO_2 emissions per capita was approximately 9 metric tons, which is almost double the world average of 4.981 metric tons [1]. The Renewable Energy Independent Power Producers Procurement Programme (REI4P) has proposed, among others, concentrating solar power (CSP) plants as one source of renewable energy to reduce the dependence on fossil fuels in South Africa [2]. This is because CSP is ideally suited to South African conditions, especially in the Northern Cape, due to the high annual average direct normal irradiation (DNI) [3].

CSP technology is present in different forms such as power towers, parabolic troughs, Fresnel reflectors and parabolic dishes. Current central receiver CSP plants require meticulous and expensive groundwork preparations such as fixing heliostats to concrete structures as well as trenching for cabling. The Solar Thermal Energy Research Group (STERG) at the University of Stellenbosch launched a project called Helio100, which was completed in 2015, introducing their HelioPod technology. As can be seen in figure 1, Helio100 is a CSP plant that uses HelioPods, which consist of six heliostats sharing a common mounting structure that is not fixed to the ground, to reflect sunlight on to a central receiver tower. Helio100 aimed to lower the cost of a small scale CSP plant by designing the system to require no groundwork or specialized skills to assemble the plant. As no groundwork is required by the HelioPod, integration of new pods into the system can occur seamlessly. The Helio100 system can be installed to provide process heat for mining, farming and other industrial processes. A steam turbine can also be added to the system to provide electricity rather than process heat.

Fig. 1. Helio100 pilot plant

A combination of wired and wireless technology is currently used in the pilot plant. The aim of this study is to explore options for wireless communication which will lower the costs of groundwork by eliminating trenching for cabling while at the same time allow rapid integration of new HelioPods into the system.

The use of HelioPods allows for a modular heliostat field

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which is state of the art compared to current central receiver CSP plants which have fixed heliostats. Research into wireless communication technology for a modular heliostat field is limited with some contributions from [4], [5] and [6].
It is expected that modern wireless communication protocols will be able to meet the requirements (such as data rates, latencies, range etc.) of a modular heliostat field and that CSP plants could benefit from the cost saving potential due to a reduction in civil capital costs.

II. CST as a technology

To convert sunlight into a usable form of energy, either photovoltaic (PV) or concentrating solar thermal (CST) systems are used. PV systems convert sunlight directly into electricity while CST systems concentrate solar radiation to create thermal energy [7]. An example of a CST system is a central receiver tower, which consists of a number of mirrors that reflect solar radiation on to a receiver, located at the top of a central tower, that converts the solar radiation into usable thermal energy.

CST technology has become popular as it offers the ability to store thermal energy that enables production after sunset. Thermal energy storage can also be used to supply a steady supply of process heat for different applications such as water desalination, manganese ore pre-heating or air drying processes. According to the national energy balance of 2015 provided by the Department of Energy, 36% of the total final consumption of energy in South Africa is consumed by the industry sector [8]. Furthermore approximately 62% of the industry sector's energy consumption was due to process heat [9].

Using HelioPod technology in a central receiver plant to supply process heat to a manganese sinter plant will result in a lower levelized cost of heat (LCOH) compared to current commercial solutions such as diesel or Brent crude oil [10]. The added advantage of modular HelioPods is that an asset is no longer fixed to a location which lowers the risks of an energy service company and allows the CST plant owner to sell process heat rather than the process plant owning and operating its own CST plant [10]. Process heating could thus be the future of concentrating solar technology as, according to the 2018 draft of the Integrated Resource Plan (IRP), there are no planned CSP plants from 2020 onwards [11].

CST plants are ideally suited to South African conditions because of the high direct normal irradiation (DNI) levels, especially in the Northern Cape as can be seen in figure 2. The highest levels of DNI is found between Springbok and Upington and are expected to be approximately 3250 kWh/m^2 per year. Due to the high DNI levels and the multiple manganese mining activities in the area, the PREMA project, which aims to advance novel energy systems in the drying and pre-heating of furnace materials, has funded a proposal for a CST plant to act as the heat source for manganese ore pre-heating.

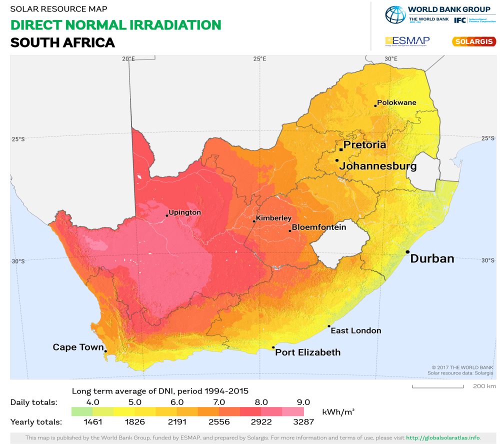

Fig. 2. Direct normal irradiation map of South Africa [12]

III. Wireless communication technology

A. LoRa and LoRaWAN

Long range (LoRa) is a radio modulation scheme developed by Semtech that is based on a chirped spread spectrum modulation [13]. LoRa uses a very efficient modulation scheme that allows long distance communication links while at the same time achieving low power usage. Long Range Wide Area Network (LoRaWAN) is a media access control (MAC)-layer built on top of the LoRa modulation scheme [13]. LoRaWAN is a popular technology in Low-Power Wide Area Networks (LPWANs) as end devices can have a battery lifetime of up to 10 years with 15 km of coverage [14]. LoRaWAN also offers a maximum raw data rate of of 27 kbps, which is sufficient for the intermittent transmitting of data from sensors that are not real-time communication dependent.

LoRaWAN defines a star topology for communication between the end node and the network gateway [15]. LoRaWAN uses the unlicensed Industrial, Scientific and Medical (ISM) spectrum for communication which is region specific (in South Africa the EU 868 ISM band is popular). ISM bands often define a maximum duty cycle of 1% for devices operating within the spectrum. This results in a maximum transmission time of 36 sec/hour for each sub band for each device operating in the EU 868 ISM band [16]. When accounting for network limitations encountered when using LoRaWAN, such as duty cycle and a 13-byte preamble, simulations from [17] have shown an effective throughput data rate over a 24 hour period of as low as 0.544 bps. As such, the maximum duty cycle is a key constraint when operating in the unlicensed ISM bands.

B. NB-IoT

Narrow Band Internet of Things (NB-IoT) is a communication technology, designed by the Third Generation Partnership project (3GPP) as part of Release 13, that operates in the licensed LTE frequency band. NB-IoT is aimed to address the needs of battery powered devices that require connection to mobile networks and thus removes certain features of

LTE such as handover, channel quality measurements, dual connectivity and carrier aggregation [18].

NB-IoT is suitable to devices requiring high quality of service, coverage of up to 35 km and data rates of up to 50 kbps [18]. The modulation techniques used in the NB-IoT technology allows base stations to be able to handle up to 200k devices. Security is also ensured by using a 128-256 bit encryption key, but there is concern as data is sent over the internet from the servers of the network operator to the final client cloud server. The major disadvantage is that NB-IoT is not deployable in regions where 4G/LTE base stations are absent. Deployment of this technology in rural or suburban regions, where CST plants are normally situated, could require a firmware change to existing base station hardware or the erection of a base station which are priced at $15000/base station [18].

C. ZigBee

ZigBee is a communication technology based on the IEEE 802.15.4 standard that is one of the most popular wireless communication standards for a wireless sensor network (WSN) because of the low power usage, low latencies and low cost [4]. ZigBee incorporates the IEEE 802.15.4 physical (PHY) and medium access control (MAC) layers and eases the inter-operability from the physical layer to the network, application and security services [19]. The different ISM radio bands that ZigBee can use to communicate between the different network components, such as the coordinator, routers and end devices, are the 868 MHz, 915 MHz and popular 2.4 GHz radio bands.

A ZigBee network is able to use both tree and mesh routing. The major advantage of ZigBee is the ability to create self-healing mesh networks which utilizes an Ad Hoc on-Demand Distance Vector (AODV) process to find the shortest communication path. This ensures no single point of failure in the communication system and alternative routes are found when one node fails. As ZigBee's range is approximately 50 m [20], multiple hops will be necessary in a CST plant. Adding hops introduces larger latencies in a communication network. ZigBee has a theoretical data rate of 250 Kbps in the 2.4 GHz frequency band and can accommodate up to 65000 nodes per network [20].

D. BLE

Bluetooth Low energy (BLE) is a communication technology designed to meet the needs of low power, low duty cycle WSN networks. BLE operates in the 2.4 GHz ISM frequency band and uses 40 channels separated by 2 MHz to communicate. BLE employs an adaptive frequency hopping strategy to counter fading and interference which allows data rates up to 1 Mbps [21].

Earlier standards of BLE (Bluetooth 4.0) only specified two different logical communication groups: a piconet and a broadcast group. A piconet is similar to a star network topology with one master node connected to multiple slave nodes. Communication is limited to being between a master and a slave node i.e. slave nodes cannot communicate directly with one another. The coverage of the network is thus limited to the range of communication between the master and slave node which is approximately 50 m [21]. Later standards such as Bluetooth 4.2 and Bluetooth 5.0 enabled slaves to be connected to more than one master and thus allowing meshed network topologies, but these standards do not define the architecture and mechanisms for formations of these networks.

E. Wi-Fi

All certified Wi-Fi products meet the IEEE's set of 802.11 wireless standards. Over the last couple of years different updates by the IEEE introduced standards such as 802.11ac, 802.11ah and 802.11ax with each having different throughput, range and battery life.

In 2013 the 802.11.ac standard, also referred to as Wi-Fi 5, was launched which used the 5 GHz frequency band for communications. Theoretical data rates for the 802.11ac standard was proposed to be over 1 Gbps, but data rates typically achieved range from 400 - 700 Mbps [22]. The 802.11ac standard expanded the 802.11n standard by adding an optional 160 MHz channel and also supporting multi-user, multiple-input, multiple Output (MU-MIMO) with up to 8 spacial streams. A feature of the 802.11ac standard called beamforming allows communication of up to 80 m even when communicating in the 5 GHz frequency band [22].

The IEEE 802.11ah standard, also referred to as Wi-Fi HaLow, was launched in 2016 to target the IoT market as well as incorporate support for machine-to-machine (M2M) devices. Wi-Fi HaLow operates in the unlicensed sub 1 GHz frequency band which enables communication ranges of up to 1 km. Data rates vary from 150 kbps to 15 Mbps depending on the communication range and bandwidth. The IEEE 802.11ah PHY layer uses channel bandwidths which range from 1 to 16 MHz. Wi-Fi HaLow allows for connection of up to 8192 low powered devices to the network as it includes advanced power saving modes, such as target wake time, to ensure longer battery lifetimes [23]. There is however no global standard for the 900 MHz frequency range that Wi-Fi HaLow operates in and as such there are no products available on the market today, even though the standard was introduced in 2016.

The IEEE 802.11ax standard, also referred to as Wi-Fi 6, is widely touted to replace the IEEE 802.11n and 802.11ac standards. Wi-Fi 6 is due to be released late 2019, although some products that are based on the draft standards are already available on the market. Wi-Fi 6 operates in the 2.4 GHz and in the 5 GHz ISM frequency bands. Wi-Fi 6 does offer an increase in speed and range when compared to Wi-Fi 5. Data rates of up to 3.5 Gbps can be expected with the added bonus that Wi-Fi 6 will be able to support distributed Wi-Fi (Wi-Fi Mesh) which allows multiple access points to connect to the main router extending the range [24]. The main focus of Wi-Fi 6 is however to increase performance in dense network operation, such as a concert or conference. Wi-Fi 6 also incorporates beamforming and MU-MIMO with 8 simultaneous streams. Orthogonal frequency-division multiple access (OFDMA) is used to divide each MU-MIMO stream into four, thus effectively increasing the user bandwidth by a factor of four [24].

IV. Network topologies

The chosen network topology within a communication network has a vital influence on different network constraints such as latency, quality of service, battery lifetime of nodes etc. Different common topologies are used such as star, tree and mesh topologies as can be seen in figure 3. Each of these topologies specify different routing paths and determines whether unicast of broadcast can be used. The choice of topology also greatly influences the packet size as well as overheads in the communication network [25]. A network topology can be evaluated according to energy consumption, scalability, redundancy, ease of deployment, latency and reaction time.

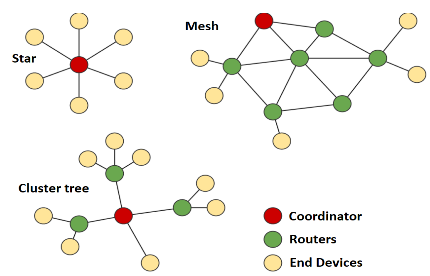

Fig. 3. Network topologies (adapted from [26])

A. Star topology

A star topology is also called a point-to-multipoint topology. It consists of a single gateway node, that acts as the central base station (CBS) in the network, to which all end devices (ED) connect. ED are used to execute quick local data processing and then transmit the data to the CBS where the data can be accessed by the end user. Each ED in a star topology is only responsible for transmitting and receiving data associated with itself which thus enables the periodic use of a low power mode on each ED when not transmitting or receiving. As a result, the energy consumption in a star network is low [25]. The limiting factor in a star network is the CBS as the scalability of the network is dependent on the amount of communication streams the CBS can manage as well as the transmit power of the CBS which influences the range of the network. The CBS is also the single point of failure in the network i.e. if the CBS fails the whole network fails. A star network topology is however simple to setup and faults are easily troubleshooted.

B. Tree topology

A tree topology is also called a hierarchical topology. Nodes are deployed in the form of a logical tree. Each node in the network, except the root node, has a parent node and potentially a child node. Communication can only occur between a parent node and its child node thus introducing a hierarchy into the network. Tree topologies allows data to be sent using unicast instead of broadcast which prevents flooding of a network [25]. Using unicast also allows for high energy efficiency of the nodes which increase the network lifespan. The major advantage of a tree topology is the ability to scale the network as an increase in range can be achieved by adding more child nodes. This will however increase the amount of hops required from the root node to the added child node which introduces larger latencies in the network. The major disadvantage of a tree node is that if a parent node fails, all the child nodes associated with it will fail as well. There are thus multiple points of failure that can lead to time consuming and costly maintenance of the system.

C. Mesh topology

A wireless mesh network (WMN) typically consists of a central network coordinator and a number of wireless nodes. Each node in the network is able to communicate with all other nodes within its communication range. Mesh networks allow up and downstream communication by incorporating algorithms such as the ad-hoc on-demand distance vector (ADOV) algorithm as used by ZigBee. Network redundancy is ensured by the self-healing ability of a mesh network which ensures a new routing path is found in the case of a node failure. Nodes can be added to expand the network without any disruption to other nodes or the need for more gateways. However, when scaling a WMN too large, latencies are introduced because of multiple hops that are needed from the coordinator to end device. Another disadvantage of a WMN is that each node in the network will drain its battery at different rates as nodes close to the coordinator will be required to relay messages more often than fringe nodes. WMN is primarily implemented where network outages are to be minimised and are complicated to setup and troubleshoot.

V. System requirements

The heliostat field is designed to meet the requirements of a 2.5 MW_t CentRec receiver, located on top of the tower [10]. The amount of heliostats required to supply 2.5 MW_t to the receiver will vary depending on the DNI at the location of the plant. According to initial modelling, a heliostat field of 1500 heliostats, or 250 HelioPods, will be required to supply the solar energy at plants with lower DNI values [27]. The proposed field layout can be seen in figure 4. Each HelioPod will be fitted with a local controller unit (LCU) which will control communication with the central field controller unit (FCU) as well as perform local calculations such as the solar position and the required heliostat normal vector. This leads to the network consisting of 250 nodes. It can be seen that the network range should exceed 80 m line of sight (LoS). It can also be seen that the heliostat field is densely packed which could introduce interference in the wireless communication network.

A target maximum tracking error of 1 mrad is proposed which requires a high level of control over the heliostats. To achieve this high level of control a short control interval is required. The current Helio100 plant uses a control interval of

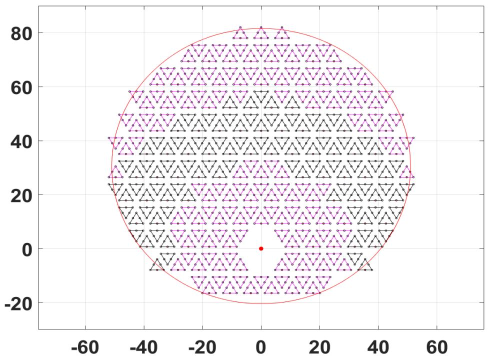

Fig. 4. Proposed field layout as seen from above [27]

1.5 s which is aimed to be lowered to 1 s in the next generation plant. During each control interval the FCU will poll the 250 nodes in the network with the date and time to which each node will acknowledge the polling by sending the individual heliostat motor counts, control status and battery level to the FCU. The proposed polling and the acknowledge message structure can be seen in table I. As each LCU is responsible for controlling all 6 heliostats fixed to the HelioPod, the acknowledge message will contain the motor counts (2 per heliostat), the status and the battery level of each heliostat which greatly influences the size of the acknowledge message payload (576 bits). Each LCU will incorporate a heartbeat timer that is designed to be reset with each polling message received from the LCU. If the heartbeat timer reaches a certain threshold time, for instance 5 seconds, the LCU will assume a loss of communication with the FCU and trigger an emergency defocus of the HelioPod. The purpose of the heartbeat timer is to avoid emergency situations where the receiver receives too much flux while the heliostats cannot be defocused. In the event of an emergency, such as a failure in the receiver or process plant, all heliostats are to be defocussed within 30 seconds which includes the time for the motors to adjust their position. The control interval to distribute the emergency message to 99% of the LCU's should take no longer than 5 seconds.

TABLE I
POLLING AND ACKNOWLEDGE MESSAGE STRUCTURE

Message Type	Data Payload		
	Data	Size [bits]	
Polling message	Date and time	64	160 bits
	Heliostat status	6 x 16	
Acknowledge message	Motor counts	12 x 32	576 bits
	Heliostat status	6 x 16	
	Battery level	6 x 16	

The polling and acknowledge (PA) process consists of 88 bytes of payload data to be transmitted per HelioPod which equates to 22 KB of payload data for the heliostat field. Several other processes such as the calibration of the heliostats, adding Heliopods to the communication network, movement specified by the heliostat field operator and the querying of error parameters for each individual heliostat would also require data to be sent over the communication system. For a conservative approach it is assumed that a further 30 KB of data is to be sent for these processes per control interval within the heliostat field. It is well known that each wireless communication protocol includes significant overheads in each frame to be transmitted such as the MAC header, inter frame spaces (IFS), Physical Layer Convergence protocol (PLCP) preamble/header and acknowledgement (ACK) transmission [28]. Using small payload transmission will result in a large percentage of the frame consisting of overheads and will degrade the throughput performance of the wireless network. The required bandwidth (BW) for the communication network is calculated using equation 1 by incorporating a conservative safety factor (SF) of 20 to compensate for the overheads incorporated in the frame. The resulting required bandwidth for the chosen wireless communication technology, incorporating a 1 s control interval (T_c), equates to 1.04 Mbps.

$$BW = SF \times \frac{(PA + OTHER)}{T_c} \tag{1}$$

VI. PROPOSED SOLUTION

The different wireless communication technologies are compared in table II. The comparison is based on a scale from 1 to 3, 1 being the lowest and 3 the highest, describing the suitability of each technology to the requirements of the CST plant. Each technology is specified a network topology as would be required if said technology is to be implemented into the proposed CST plant. Using a mesh network for example increases the range of a ZigBee network to achieve the 80 m range requirement of the CST plant, but will introduce large latencies due to the multiple hops from FCU to the furthest LCU. Ease of implementation is influenced by factors such as availability of devices, use of licensed frequency bands and network topology.

TABLE II
TECHNOLOGY COMPARISON

	LoRa	NB-IoT	ZigBee	BLE	Wi-Fi 5	Wi-Fi 6	Wi-Fi HaLow
Topology	Star	Star	Mesh	Mesh	Tree	Star	Star
Range of individual module	3	3	1	1	2	2	3
Bandwidth	1	1	1	1	3	3	3
Energy consumption	3	3	3	3	1	2	3
Latencies of network	1	3	1	1	2	3	3
Ease of implementation	3	1	1	1	3	2	1

All discussed topologies have the common central point of failure which is the FCU. It is thus inevitable that if the FCU fails then the whole field will shut down. The network topology is selected to minimise the points of failure while at the same time ensuring low latencies and high data transfer rates within the system. A star topology is selected for the system as it eliminates the use of clusters, which could see a cluster shut down with a single router failure, and also ensures lower latencies compared to a meshed network topology. The star network topology also allows easy and quick integration of new HelioPods into the network.

The Wi-Fi 6 or 802.11ax standard will be the optimal wireless standard to use in the system. As Wi-Fi 6 is designed to operate in dense networks such as the CST plant in question. Wifi 6 incorporates 8x8 uplink/downlink MU-MIMO and OFDMA to enable higher transfer rates to more devices in a dense network. Wi-Fi 6 also incorporates a procedure called basic service set (BSS) coloring which addresses the problem of co-channel interference (CCI). BSS coloring enables Wi-Fi 6 to efficiently reuse spectrum in dense deployment scenarios by identifying which transmissions are from a different BSS. BSS coloring will allow transmission if the transmitted signal is not from the BSS in question i.e. has another BSS color. This procedure greatly reduces bottlenecks in the network and thus produces lower latencies. Wi-Fi 6 also allows for theoretical data rates of up to 3.5 Gbps which could be increased to 14 Gbps when using 160 MHz channels with 4x4 MIMO streams. In this application 20 MHz channels are to be used in the 2.4 GHz ISM frequency band to increase the number of clients as well as the transmission range, which is expected to be further than the corresponding 802.11n's (Wi-Fi 4) outdoor range of approximately 90 m due to beamforming procedures, while throughput data rates of up to 290 Mbps can be expected [29]. Wi-Fi 6 also incorporates target wake time (TWT) which will greatly increase the battery lifetime of client devices. Client devices are expected to be arriving in 2020.

VII. Conclusion

CST as a technology is an attractive option to reduce power consumption where process heat is needed. By incorporating the HelioPod technology a modular heliostat field can be designed. In this article different methods of wireless communication are explored for the heliostat field such as LoRa and LoRaWAN, NB-IoT, ZigBee, Bluetooth low energy (BLE) and Wi-Fi (Wi-Fi 5, Wi-Fi 6 and Wi-Fi HaLow). In the proposed solution the newly developed 802.11ax standard or Wi-Fi 6 operating in a star topology is touted as the best solution for the communication network. This solution promises high data transfer in a dense network environment while at the same time also offering sufficient range as well as battery lifetime of the client due to new technologies such as OFDMA, TWT, beamforming and BSS coloring.

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