Cyclic Beam Switching for Smart Grid Networks

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***Abstract*—In the future, data will be collected from a wide range of devices (the Internet of Things or IoT). This may be from simple transmit only devices such as sensors or devices with two way communications so control information can be sent to the device. A Smart Grid depends on such an infrastructure since it is used to collect energy usage data which is then used for billing as well as to make decisions for the power grid or to control individual locations (e.g., to increase air conditioner temperature settings when a brownout is imminent). Typically, in these networks, most of the communication is in the uplink direction. Furthermore, high reliability and low latency is required but with minimal network infrastructure cost. In this paper we investigate the use of Cyclic Beam Switching for the case of an Advanced Metering Infrastructure used, for example, in Smart Grids. The proposed approach is simple with little additional cost and one can significantly increase the coverage area while maintaining acceptable reliability and low latency.**

***Index Terms*—Beam Switching, Smart Grid, 5G, IoT, Network Optimization, AMI, Advanced Metering Infrastructure**

I. INTRODUCTION

In an Advanced Metering Infrastructure or AMI system, Smart Meters (SM) are placed in customers' homes and these transmit energy usage information at periodic intervals to a Cell Control Unit (CCU) over a wireless network [1], [2]. These readings are typically used for billing the consumer for electricity usage. The payloads of these reports are small but, because of limited transmission power of the SMs, the number of required CCUs can be significant. The density of these CCUs is a major cost component of the AMI and hence any reduction in density is desirable. This is particularly true is rural areas where the density of SMs is low but the same density of CCUs is required to capture all readings. In this paper we propose the use of Cyclic Beam Switching (CBS) as a low cost means of reducing the number of CCUs required in rural or low density areas without increasing the number of SMs.

For this paper we make certain assumptions on technologies but the basic approach is applicable to a wide range of wireless technologies. We assume that the uplink technology is SC-FDMA (Single Carrier Frequency Division Multiple Access) as is used in LTE (Long Term Evolution) [3]. The approach will work with other technologies but to simplify the discussion we focus on SC-FDMA. It is envisioned that, in the future, power companies will use Unlicensed band LTE or U-LTE [4] for providing these types of data collection services. The next cellular standard (5G) will also be designed with IoT in mind. In SC-FDMA the bandwidth is segmented into Resource blocks (RBs) and one or more of these is allocated for use by one or more devices. Transmissions may require one or more time slots (frames) for transmission. Since the payload is small then the resources required for a reading transmission (RBs and slots) is small and hence we can safely assume that the system is not resource limited (i.e. there are sufficient resources to support all SMs). The system capacity is in fact limited by the range of the SM transmissions (i.e., the CCU cell radius) because of their limited power. One way to improve coverage is to use sectorization whereby the cell is broken into sectors and each sector has its own directional antenna and transceiver. However this option can be costly. Increasing bandwidth resources also does not help if the received signal strength is too weak.

In CBS, beams are electronically formed and continuously switched in some predetermined pattern. Note that in this case we use a single transceiver since only one beam (or a subset of beams) is processed at a time and all transmissions during this period are assumed to be orthogonal (i.e. SMs transmitting during this period use different RBs and or slots). Since we are considering the uplink, this means that once a beam is formed it must be used to receive transmissions from all SMs within the footprint of that beam. Hence this requires synchronization of the SMs which we discuss later. Note that that SMs themselves still transmit in an omni-directional fashion.

Although Cyclic Beam Switching has been proposed for the LTE downlink for periodic services, such as VoIP, [5] it has not been proposed for an AMI. The paper [6] does include beamforming but the focus there was on using Cognitive radio and not on capacity increase. The paper [7] considers how CoMP (Coordinated Multipoint transmissions) as proposed in LTE can be used. With CoMP multiple Base Stations coordinate their transmissions (uplink or downlink) in order to constructively use ”interference”. However such approaches require communications between Base Stations (equivalent to CCUs in our case). Such communication does not exist in typical AMIs and hence its implementation would require additional expense.

In the next section we provide the model used for our analytic results. We then provide simulation results under more realistic assumptions. Finally we discuss the results and show the benefit the approach provides with little additional cost.

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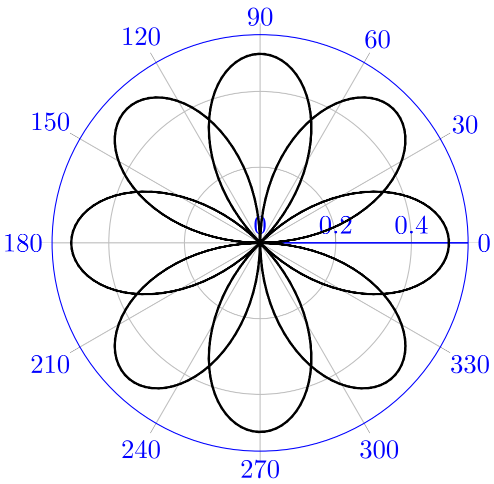

Fig. 1. Beams for a Circular Antenna Array

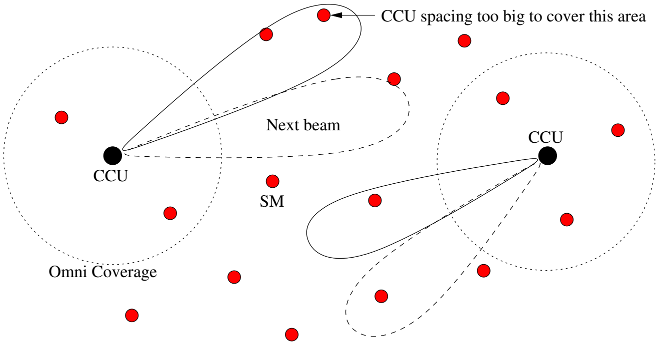

Fig. 2. Beamswitching Illustration

II. CYCLIC BEAM SWITCHING

Our objective is to provide a simple solution the CCU density problem. We therefore assume a circular antenna array and that beams are electronically controlled for reception of transmissions [8]. The number of possible beams increases with the number of antennae in the array. For example, we can have eight possible beams as depicted in Figure 1. As the number of beams is increased, their length increases and hence the antenna gain increases. We therefore assume that the the antenna gain increases linearly with the number of beams with the omni-directional antenna (a single beam) having a gain of unity.

In Figure 2 we illustrate the case of two neighbouring CCUs. The circle around each CCU represents the coverage of an omni-directional antenna while each beam represents the coverage of that beam. While a beam is active only transmissions from SMs within the beam are received at the CCU. Note that, in this example, the CCU spacing is too big to cover all SMs. However if we look at the area covered by the union of all beams then it includes all SMs.

We assume that while a beam is active all SMs within the beam transmit and hence coordination of the SM transmissions is required. Since SM transmissions are periodic then the period of the SM transmissions must be a multiple of the beam switching period. We will assume that both periods are identical so that each time a beam is formed then all SMs in the beam transmit. This coordination is achieved as follows. Based on the GPS coordinates of a SM we first determine its closest CCU. For the chosen CCU we then determine which beam covers the SM. We then assign a free RB to that SM in any of the time slots available while the beam is active.

III. ANALYTIC RESULTS

In this section we propose a mathematical model for the problem and provide analytic results. In SC-FDMA, uplink resources are allocated in Resource Blocks (RB). Each RB spans a number of frequencies and lasts for a Transmission Time Interval (TTI) which is typically 1ms. We denote the bandwidth allocated to a transmission by b and the transmission time by unity. Furthermore we assume that B RBs are available so the maximum number of supported users is B/b.

Since there are many SMs and each is transmitting then one can consider the uplink interference as a part of the background noise since no single SM can significantly affect the interference at any CCU. Later we will discuss the effect of increased interference with increased SMs. We consider a single CCU and compute its user capacity under the assumption that all SMs not within the CCU's cell contributes constant interference. Each SM transmits with constant power and, for simplicity, we denote the ratio of this power to the constant interference and noise by P. Note that this is for the omnirectional antenna case. If we use k beams then the signal energy received at the CCU will be increased by a factor of k because of the antenna gain. Since repetition coding will be used we ignore fast fading and only consider path loss with a loss exponent of α. Note that Shadow Fading is not considered for the analytic results but will be included for the simulation results.

Reports from all SMs are identical and consist of M bits. We assume that sufficient resources (power, bandwidth and time) are allocated to each transmission so that some target success probability is achieved. With k beams we denote the distance to the cell edge by r_k. As the number of beams increases, the antenna gain for a beam increases and so the cell edge distance increases. We use the Shannon Capacity formula to compute the rate achieved at the edge and multiply by the transmission duration to obtain the number of bits received. Therefore we have:

$$M = b \log_2(1 + kPr_k^{\alpha}) \qquad (1)$$

where the received power is increased by k to reflect the antenna gain and the path loss is given by r_k^{α}. We can therefore compute the ratio of the cell radius for the case of k beams and one beam (omnidirectional) as

$$\frac{r_k}{r_1} = k^{-\frac{1}{\alpha}} \qquad (2)$$

Now note that the system can also be resource limited if the resources needed for the cell population exceeds what is available. Hence sufficient resources will have to be made available for the worst case scenario (e.g., urban environment). For a population density of λ let us assume that the exact number of resources are provided so that

$$\frac{B}{b} = \lambda \pi r_1^2 \tag{3}$$

Now if we consider less dense areas (rural areas), the cell spacing (and hence cost must remain the same) and the number of resources will also have to be the same (for planning purposes). Hence in rural areas there will be excess resources but the infrastructure cost remains the same. Now with CBS we can have greater cell spacing in the rural areas and so serve more users per cell thus using up the available resources. The CCU density grows inversely with the square of their spacing. Since the infrastructure cost grows approximately linearly with the CCU density then the costs for a k beam infrastructure compared to an omnidirectional infrastructure is given by

$$\frac{J_k}{J_1} = \frac{r_1^2}{r_k^2} = k^{\frac{2}{\alpha}}$$

where we used Equation 2

We can also compute the population density required for a k beam infrastructure to become resource limited. Let λ_k denote this value then

$$C_r = \lambda_1 \pi r_1^2 = \lambda_k \pi r_k^2$$

and hence

$$\frac{\lambda_k}{\lambda_1} = \frac{r_1^2}{r_k^2} = k^{\frac{2}{\alpha}}$$

which is the same as the cost ratio.

In Figure 3 we plot the cost ratio and density ratio (which are the same) as a function of the number of beams used. We used a path loss exponent of $\alpha = -3$. As the density decreases (very sparse areas), more beams can be used and more cost savings achieved. For example assume that in a city environment the resources allocated to a CCU are chosen so that it is equal to the number of resources required by the SMs in the coverage area of the CCU. If we consider a rural area with a SM density of 25% of the city SM density then one can use CBS with eight beams to cover a wider area and be able to use all available radio resources for the service. By doing this the infrastructure cost would be 25% of that of the omnidirectional antenna case.

In the above analysis we assumed that the interference experienced (which was combined with the background noise) was constant. However as the SM density decreases, the interference decreases. In our model as the density decreases the number of beams increases and hence the interference used in our model for the multi-beam case is an upper bound. This means that the performance for the multi-beam case is actually better than what is obtained from the analysis.

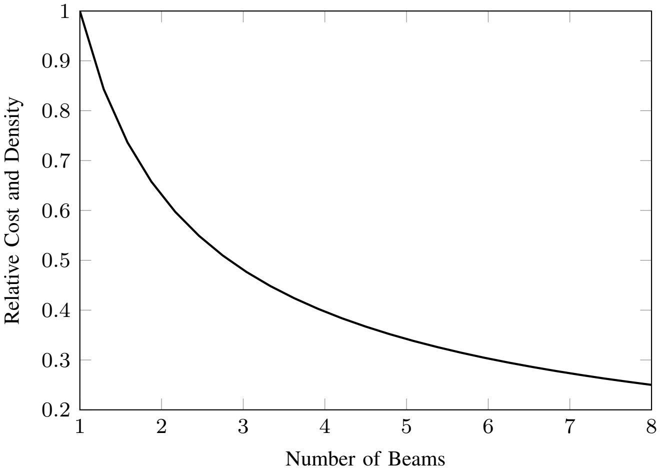

Fig. 3. Relative Cost and Relative Density as a function of Number of Beams

IV. SIMULATION RESULTS

We simulated a simple scenario and included fast fading effects, Shadow fading and also path loss. The network considered consisted of nine CCUs and we focused on the performance of the CCU at the centre. The eight surrounding CCUs were used to generate interference to the centre CCU. Figure 4 depicts the locations of CCUs and transmitting SMs during one period of the beam switching cycle. The testing parameters were specified such that a typical spectral efficiency was achieved given the assumed technology. The interference contributed by each transmitting SM of the surrounding CCUs was calculated. The number of beams were varied between 1 and 8. The cell edge distance achieved by increasing the number of beams was determined for each case. The ratio of the cell radius for the case of k beams and one beam (omnidirectional) was computed. The resulting cost ratio which is the same as the density ratio is shown in Figure 5. The test scenario was examined after the spacing of the CCUs were varied. The resulting cost ratio and density ratio was not affected by the spacing of the CCUs or interference contributed by the transmitting SMs.

V. CONCLUSION AND FUTURE WORK

In this paper we considered the problem of reducing the cost of an AMI network through the use of Cyclic Beam Switching. We showed that, as the density of SMs in an area decreases, one can increase the number of cycled beams so as to increase the coverage of each CCU. Because of the smaller SM density, the increased coverage area results in the same number of captured SMs as achieved in denser areas and hence the number of radio resources (Resource Blocks and time slots) are sufficient even with the larger coverage area. The proposed approach can be applied to other radio technologies and simply requires a circular antenna array with electronically switched beams.

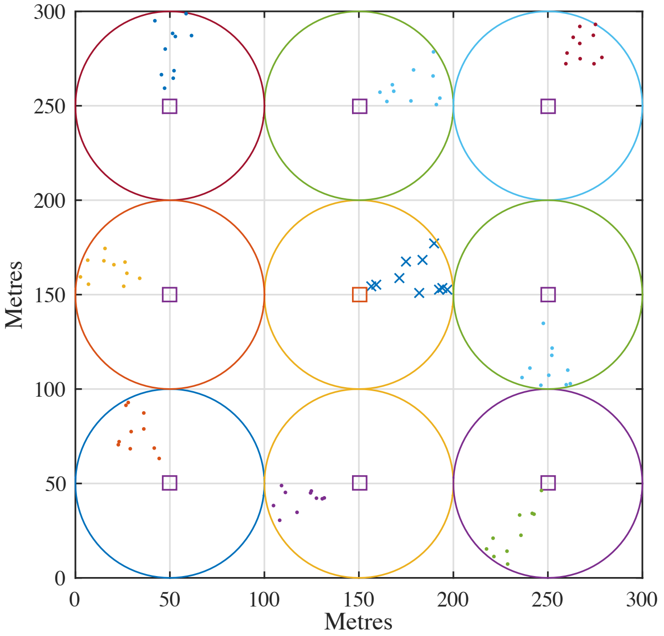

Fig. 4. CCUs and transmitting SMs used for Simulation

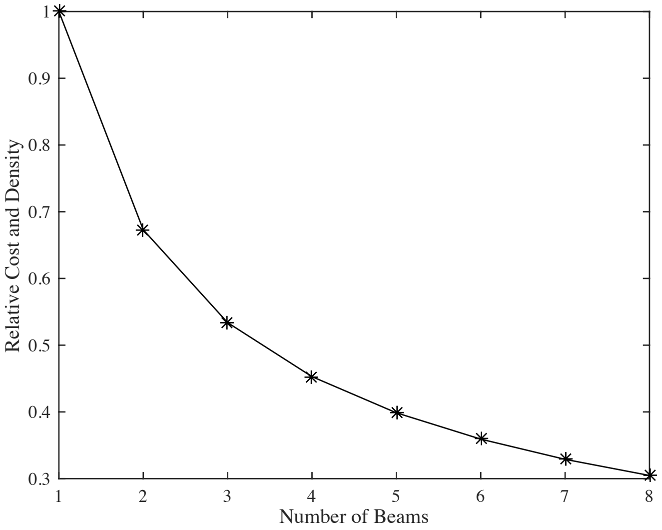

Fig. 5. Relative Cost and Relative Density as a function of Number of Beams

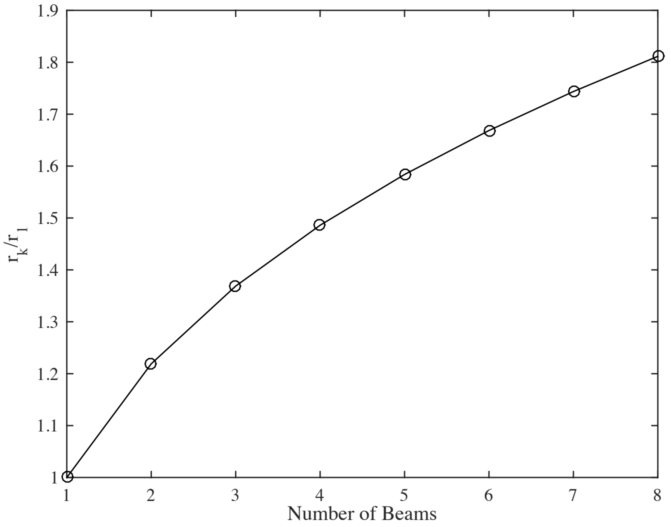

Fig. 6. Ratio of Cell Radius for k Beams and One Beam

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