Optimization and Scheduling of Queueing Systems for Communication Systems: OR Needs and Challenges

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Abstract: The modern communication system is growing at an alarming rate with fast growth of new technologies to meet current and future demands. While the development of devices and technologies to improve and meet the expected communication demands keeps growing, the tools for their effective and efficient implementations seem to be lagging behind. On one hand there is a tremendous development and continued advancement of techniques in Operations Research (OR). However it is surprising how the key tools for efficiently optimizing the use of the modern technologies is lagging behind partly because there isn't sufficient cooperation between core OR researchers and communication researchers. In this position paper, using one specific example, we identify the need to develop more efficient and effective OR tools for combined queueing and optimization tools for modern communication systems. OR scientists tend to focus more on either the analysis of communication issues using queueing theory tools or the optimization of resource allocations but the combination of the tools in research have not received as much attention. Our position is that this is one of major areas in the OR field that would benefit communication systems. We briefly touch on other examples also.

1 INTRODUCTION

The demand for communication systems keeps growing on an ongoing basis. Communication industry researchers are continuously working at coming up with new technologies for meeting the demands. In a recent ACG Research report (ACG, 2015) it was pointed out that for an area of 1,200 square kilometer metro area having approximately a population of about 2.5 million people the bandwidth requirement for backhaul at a cell site could be as high as 2.5 Gbps in the year 2018 and about 10 Gbps of Ethernet links and 10 Gbps rings to meet the demand requirements and support the expected growth. Part of these growths in demand have to do with the shifts in customers to data. In the past media and video was less than 10% of the traffic and now it is almost 50% according to the recent Global telecommunications study: navigating the road to 2020 (EYReport, 2015). Bandwidth available is limited however efforts are been made to squeeze more from what is available and also to release some inefficiently utilized radio frequencies for other uses. Hence telecommunication engineers do not only have to ensure that they could provide the capacity for these demand growths but make sure also that the capacity is efficiently well managed.

In trying to provide efficient and effective communication services for the future we need to harness several key tools mostly OR based. Our position is that this has not received the proper attention it deserves from the OR researchers and practitioners. The aim of this paper is to try, with the aid of some examples, to identify the major role that OR researchers can play in planning modern communication systems.

Historically queueing model by itself has been extensively used in analyzing the performance of communication systems. In fact to the extent that when people talk of performance analysis in communication systems they are most likely referring to queueing model analysis of a communication system. Often the model is for a particular protocol. A protocol, in simple terms, is the rule by which a system operates. When the protocol for a system changes, the queueing system that represents it changes and hence the system would need to be re-modelled in order to obtain its performance. Keeping in mind that a communication system designer may have a plethora of

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possible protocol designs for a particular system, deciding on the "best" design becomes an exercise of modelling and evaluating the system with each protocol and evaluating it. This could be a nightmare of combinatorial problem. The ideal thing would be to be able to develop a combined queueing and optimization model where the parameters of the queueing system are to be decision variables in the optimization problem and a performance measure of the system is the objective function. This is straightforward enough. However when we look at the literature on this subject the research on the topic lags behind considerably in meeting the challenges of appropriate mathematical modelling of the modern communications needs. That is why we have decided to further bring this to the attention of OR researchers and analysts.

2 COGNITIVE RADIO NETWORKS

Cognitive radio networks (CRN) is one of those technologies that is being pursued as a way to increase capacity for communication. CRN emerged from the observations of some researchers and the FCC (Federal Communications Commission) that some of the licensed frequencies, especially the TV band, are underutilized. As a result CRN is a network in which when the primary user (who has license for a particular channel) is not using it a secondary user may try and access it provided it does not interfere (beyond a tolerable limit) with the primary user. For more details about this technology and associated background see (Mitola and Maguire, 1999) and (Haykin, 2005).

In CRN a secondary user (SU) senses a channel and may access it if it is not in use. We call this access approach the overlay. However if the channel is in use by the primary user (PU) the SU may still access it if the SU can transmit at a power level that will not interfere with the PU. This we call the underlay. The methods for sensing the channels are well documented in the communication literature.

The question here is when a channel can be accessed by SUs how does the system decide on which SU to access which the channel and for how long. This becomes a major queueing and optimization problem which is better addressed by using OR tools. In the next section we show how OR tools can be considered as tools for this and the challenges involved.

In real life there are several channels involved in communication systems. However to make it simple for expositional purposes we consider a single channel model for CRN. Later we discuss how the multiple

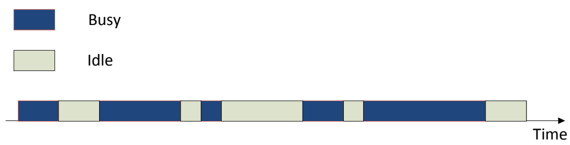

Figure 1: Busy and Idle times (single channel).

channel cases are studied.

Consider a single communication channel used by one or several PUs. For simplicity let us assume that the PUs arrive according to a Bernoulli process with parameter λ_p and the channel can process at geometric distribution with probability μ. Keep in mind that the PUs required processing rate could be $\mu_p < \mu$. This system can be studied as the Geo/Geo/1 queue. Even if the arrival and processing processes are not simple we can still analyze the system using a single server queueing model. We chose to work in discrete time because modern communication systems are digital. Further consider a case on one channel licensed to a PU which is either busy or idle. We can represent it as an alternating stochastic process $\{busy, idle\}$. A simple example of that is an alternating Markov renewal. For the sake of explaining we consider the special case of Markov chain, with two states $\{0,1\}$ where 0 represents busy and 1 represents idle. Let X_n be the state at time n and define $P_{i,j} = Pr\{X_{n+1} = j, X_n = i\}, \forall n$ then we can write the transition matrix of this system as

$$P = \begin{bmatrix} p_{0,0} & p_{0,1} \\ p_{1,0} & p_{1,1} \end{bmatrix}$$

The following diagram (Fig. 1) is a schematic representation of idle and busy periods of this channel.

If we now introduce an SU with arrival probability λ_s, this SU may try and access the channel using the overlay or underlay schemes.

2.1 Overlay Scheme

In the overlay scheme, the SU will only access the channel when it is idle and has to vacate it when the PU returns to the channel, i.e. when it becomes busy again. So in essence an SU sees this channel as a vacation queueing system in which the server (channel) is on vacation when it is busy with the PU. The SU can thus only be served during the queues idle period (when the PU is not occupying it). This is a queueing problem which can be analyzed using standard queueing models. This problem is quite straightforward if all we have is just one SU trying to access the channel. The SU just waits for the time it detects the channel to be idle and then access it. The point in time when

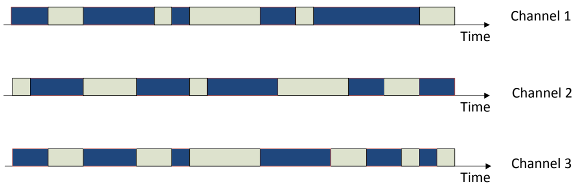

Figure 2: Busy and Idle times (multiple channel).

the channel becomes idle is a point process and the duration of the idle period is stochastic.

The question that arises then is when we have more than one SU waiting to access the channel; how do we allocate the channel to the SUs? What priority schemes do we use? This calls for an optimization tool for scheduling the SUs. Keeping in mind the stochastic nature of the idle and busy periods of the channel a system scheduler has to implement an efficient scheduling procedure. Now if we have multiple channels, which is more realistic, then we are dealing with a system of superposition of several of the channel Markov chains. For simplicity let us assume that the channels are identical with the same Markov chains with representation P, then the resulting Markov chain that represents all the K channels has Markov chain with transition matrix P_K written as

$$P_K = P \otimes P \otimes \cdots \otimes P,$$

where there are K Kronecker products of the matrix P , i.e. $P_K = \bigotimes_{j=1}^{K} P$. A good diagrammatic example of the busy and idle channel behaviours of this can be demonstrated by the case of $K = 3$ in Fig. 2.

In this case we need to keep track of which queue (channel) is idle and which one is busy at all times. Selecting which channel to assign to which SU is a challenging dynamic assignment problem; scheduling when to let a particular SU access a channel is also a challenging OR problem, especially if we assign a group of channels to some SUs ((Jiao et al., 2011; Jiao et al., 2012)).

Finally there are usually some SUs that have high data transmission rate and often are willing to pay for superior service. Such SUs require that more than one channel are assigned to them ((Jiao et al., 2011; Jiao et al., 2012)). How do we develop an optimization to handle this type of problem? For example, consider the case of three identical channels above. If we have say three SUs, and one of them requires two channels while the third channel is shared by the other two, how do we decide which two channels to assign to this special SU? There are three possible ways, all dependent on the stochastic process describing the channels. One just has to imagine what happens when we have $N\,(N >> 1)$ channels and $M\,(M >> 1)$ SUs with the i^{th} SU requiring m_i channels. . Even for the

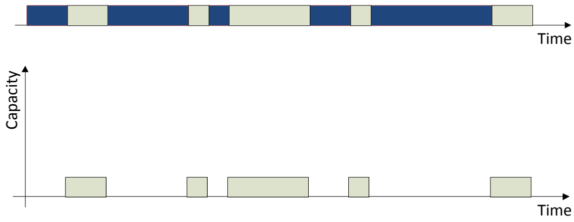

Figure 3: Capacity (single channel).

case when $\sum_i^M m_i \leq N$ it could still be a major combinatorial problem, combining queueing and optimization.

These are some of the issues that arise in the CRN technologies, and which we think can benefit tremendously from the OR communities.

2.2 Underlay Scheme

Dealing with the underlay scheme is about the same as the overlay scheme except that we now have to also allocate a power level to an SU to ensure that it does not interfere with a PU transmission. So the additional question here is what power level should we assign to an SU and to which SU in order to maximize communication capacity?

In addition we may also be in a position to have a hybrid scheme in which some SUs are placed on overlay scheme, some on underlay scheme and some on a combination of both. The question is how do we determine which ones to assign what scheme and how? This is an optimization problem which also has impact of the network performance.

Let us first look at the case of one channel in which an SU wants to consider underlay in addition to overlay, i.e. a hybrid. For the one channel even though we may know the busy and idle period, during the idle period we know that an SU can transmit at its full power (if possible), if it is the only one transmitting. However if it wants to transmit also under the underlay scheme the power level allowed may vary depending on what is the level of power of the PU. We present a schematic diagram of the situation under full capacity below in Fig. 3, i.e. when the channel is idle. For the case of underlay,he available capacity cannot be higher than what is shown in Fig. 3.

If we now consider the case of three channels, superimposed and then capturing the combined capacity we may have a case like the one below in Fig. 4.

How to now assign the channels and power becomes a major queueing, assignment and scheduling problem which is not as straightforward.

In what follows we introduce a small generic resource allocation problem and use that as the basis of our discussions in comparing the papers in the liter-

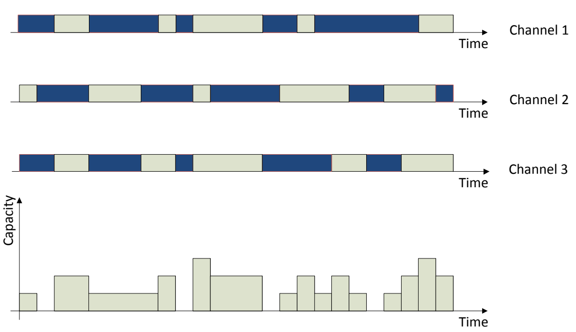

Figure 4: Capacity (multiple channel).

ature. Consider a simple CRN problem in which we have K PU channels. There are M SUs looking for access to the PU channels. Each SU, $s = 1,2,\cdots,M$ has a maximum power source of P^s_{max}. If SU s is allowed to transmit on channel k with power level P^s_k, then its capacity, c^s_k will be given as $c^s_k = \log\left(1+\gamma^s_k P^s_k\right)$, where γ^s_k is the noise level associated with SU s transmitting on channel k. This is essentially a simplified Shannon's capacity formula or a formula derived from it. Whether we are dealing with capacity, throughput or data rate a version of this formula is what we use.

Let $x^s_k = 1$ if channel k is assigned to SU, s and zero, otherwise. Generally the throughput and data rate resulting from this are directly proportional to this capacity. So in essence the total capacity assigned to this SU, s will be

$$z_s = \sum_{k=1}^{K} c^s_k x^s_k.$$

In RA problem our interest would be to maximize the total weighted capacity for all the SUs, with the weight w_s assigned to SU s. Hence the objective function of this generic problem will be

$$\max\ z = \sum_{s=1}^{M} w_s \sum_{k=1}^{K} c^s_k x^s_k. \tag{1}$$

This is a non-linear function in P^s_k and x^s_k.

Next we consider the constraints. The first one is that we want to ensure that at least one channel is assigned to an SU, on the assumption that $M \leq K$. So we need the constraint

$$\sum_{k=1}^{K} x^s_k \geq 1, \quad \forall s = 1,2,\cdots,M, \tag{2}$$

and also a constraint that ensures that we do not assign more than a channel to more than one SU, i.e.

$$\sum_{s=1}^{S} x^s_k \leq 1,\ \forall k = 1,2,\cdots,K. \tag{3}$$

The next constraint is that we cannot allow the total power generated by an SU to exceed its power limit. So we need the constraint that

$$\sum_{k=1}^{K} P^s_k \leq P^s_{max}, \quad \forall s = 1,2,\cdots,M. \tag{4}$$

A key requirement in CRN is that the SU should not interfere with the PU, or at least the interference should not exceed the maximum allowed level. This can be easily captured by requiring that the power reaching the PU should not exceed a particular value $P_{\mathbf{power}}$. So the next constraint is

$$\sum_{s=1}^{S} \sum_{k=1}^{K} P^s_k \gamma^s_k \leq P_{\mathbf{power}}. \tag{5}$$

with the variables allowed to assume any non-negative values.

Given that SUs usually have a minimum requirement for QoS we assume that there is a constraint in this regard also. For example, an SU, s, may require a minimum of σ_s of total capacity after combining a number of sub-channels assigned, so this leads to the constraint

$$\sum_{k=1}^{K} x^s_k c^s_k \geq \sigma_s, \quad \forall s = 1,2,\cdots,M. \tag{6}$$

Finally we have the two critical but common constraints, i.e. that of zero-one on x^s_k and non-negativity on P^s_k, both written as

$$x^s_k \in \{0,1\}. \tag{7}$$

$$P^s_k \geq 0. \tag{8}$$

In summary, Equations (1) to (8) form the resource allocation (RA) problem for this simple example. As one can see, in its simplest form, the objective function in non-linear, and constraint (6) is non-linear. Also one variable, x^s_k is zero-one while P^s_k is a simple non-negative variable. So unless there is a significantly different problem studied, non-linearity and integer variables (zero-one) are unavoidable in the formulations. That is why in general we have a non-linear mixed integer programming problem for RA. The issue now is how it has been handled in the literature. A more detailed discussion of this can be found in (Alfa et al., 2016).

It is however important to point out some aspects of this formulation that could be further improved to reflect an attempt to truly optimize the system as a whole. We know that the resulting capacity available to an SU, after the optimization, determines the delay or latency of packet transmission. So we need to incorporate additional constraints, based on queueing models, that limit the delay or add a delay cost component to the objective function. These are usually not incorporated in the RA models because of the complexity it would introduce to the problem. This is one major reason why it is important for the communication system researchers and OR analysts/researchers need to collaborate on carrying out major complete model analysis.

SUGGESTED IDEA FOR COLLABORATION:
Telecommunication researchers often resort to the use of simple heuristics to quickly obtain solutions to the type of optimization problems discussed above. The heuristics are usually not rigorously studied before implementation. For example, exploring and understanding how "good" the solutions are is very important especially now that there is a need to "squeeze" as much as possible from the network. Solutions that are not proven to be efficient, for example if the gap between the solution and the bound is large, could be misleading. This is where it is very important for the telecommunication researchers to collaborate more with OR analysts whose interests, capacity and experience are in these aspects. The OR analysts on their own, would probably have more interests in the mathematical analysis of the system and looking for bounds. In the process may assume away some important aspects of the problem which a telecommunication researcher knows is very important for the problem. That is why the two groups need to collaborate and work together in coming up with better solutions. The combined collaborative effort of the two groups would lead to much better solution.

3 WIRELESS SENSOR NETWORKS AND THE INTERNET OF THINGS

The Internet of things (IoT), which is probably more correctly be termed the Internet for Things (IfT) as suggested by Kevin Ashton, the originator of the term IoT (Peter Day's World of Business, 2016 (BBC, 2016)), is seen as one of the technologies that would drive our daily activities and hence very important. To quote the Wikipedia,"IoT is the internet working of physical devices, vehicle, building and other items embedded with electronics, software, sensors, actuators, and networking connectivity that enable these objects to collect and exchange data". It is immediately clear that one of the technologies that would enable the IoT is wireless sensor networks, among many other technologies. A wireless sensor network (WSN) is a self-organizing network that consists of a number of sensor nodes deployed in a certain area. The sensor nodes basically sense and acquire data from the environment, process data for storage, as well as a communicate (transmit) the data to a sink node. It is the communicated data that the IoT system uses to actuate activities in response thereby generating device-to-device activities. With the new 5G technology in discussion it is believed that the IoT will drive most of actions and activities from smart cities to smart grid, to smart health, environmental monitoring, infrastructure management, manufacturing, energy management, city management, home and building automation, transportation, etc. So first we consider the role of OR in sensor networks modelling and analysis.

3.1 Wireless Sensor Networks

There are a number of different applications of sensor networks in areas such as environmental monitoring, industrial control, disaster recovery, and battlefield surveillance. The major constraint in large scale deployment of WSNs is the limited capacity of processing, storage and energy of the wireless sensor nodes. It is important that the buffer capacity is sufficient to avoid data loss, that the processing capacity is high enough to obtain very good latency, especially for time sensitive data for the Internet of Things, and most important is that processing is limited to times when the system can be utilised efficiently, i.e. energy is conserved through the sleep/awake management of the sensors. In order to effectively carry out the design of many aspects of sensor networks, a very good queueing analysis is important. Queueing theory plays a major role than has been emphasized in the literature.

WSN is a collection of several nodes of sensors of all types connected via wireless channels of different capacities with varying channel conditions. The sensor nodes are usually of different capacities and different functionalities. Some of them collect, process and transmit data, and others only carry out a few of the functions. Let us denote by $\mathcal{N}$ a set of sensor nodes where $N = |\mathcal{N}|$ and $\mathcal{N} = \{N_1, N_2, \cdots N_N\}$. Let $\mathcal{A}$ be the set of channels connecting pairs of sensor nodes. For example, let $A_{i,j}$ be a connection between sensor nodes N_i and N_j, then $\mathcal{A}$ is the set of all those channels. Let $C_{i,j}$ be the capacity associated with channel $A_{i,j}$, and K_i as the buffer capacity and P_i as the processing capacity associated with sensor node i. We can therefore say that a WSN can be

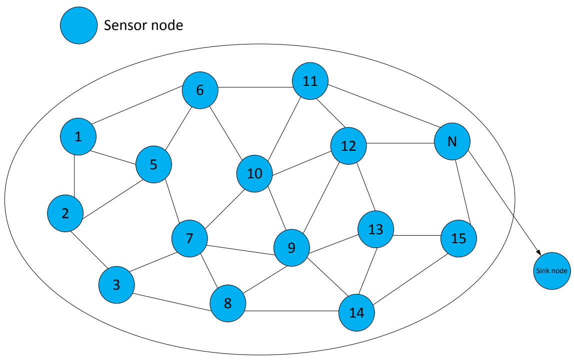

Figure 5: Sensor node distribution.

described by a network $G = \{\mathcal{N}, \mathcal{A}\}$ with attributes $\{(K_i, P_i), (C_{i,j}), i \in \mathcal{N}, (i, j) \in \mathcal{A}\}$. See Fig. 5 as an example.

1) Queueing Aspects of WSN: The first thing one notices about WSN is that it is like a network of queues with each sensor node representing a queueing node. Since data arrival is usually not necessarily Poisson type, and more often kind of correlated, simple single node queues or even simple queueing network models such as the Jackson networks are not appropriate for modelling the WSN. In addition, given that we need to include sleep/awake mode scheduling the model then becomes more complicated. This calls for more sophisticated and more representative queueing models, the types that queueing theoreticians do not seem to have focused on yet. Considering queueing models that assume non-renewal types of arrivals with bursty instances is more appropriate. However then including such processes in a queueing network, which is beyond the Jackson's model, is a challenge which queueing theorists need to tackle.

2) Power Management of WSN: Due to the fact that most sensor nodes are battery operated, i.e. have limited available power source, it is important to efficiently manage them effectively for a long lasting network life. Usually a sleep/awake mode is implemented to achieve this goal; a very good vacation queueing model in which the scheduling of the sleep/awake mode is well controlled. This involves a combined queueing model with optimization techniques. Queueing theory can prove to be an effective tool to analyze and design efficient power allocation schemes to increase the power efficiency of WSNs (see (Kabiri et al., 2014)). Sleep/awake models are based on special kinds of vacation models. When the sensor goes to the sleep mode, that means it is switched off and cannot process data. This is essentially a vacation model. Data arrivals accumulate at the buffer. The node wakes up depending on the time which is based on a policy of how many packets are waiting (N), how long they have been waiting (T) and the total amount of Kilo-bytes of data (D). These models are classified as N-policy, T-policy or D-policy models. Recently there have been combined versions of these models, such as the NT-policy, and there are research activities going on regarding developing ND, and NDT-policies. Sleep/wake-up schemes essentially makes use of duty cycle schemes which are used to wake a node up from an idle state to the busy state by turning on the radio server. This plays an important role in the level of power savings in the context of MAC protocols. The authors in (Kabiri et al., 2014) derived an analytical model utilising a M/G/1 queue to model the sensor node; and by altering the queue parameters, different sleep/wakeup strategies were analysed. Some IEEE 802.11 MAC protocols like the sensor MAC, sparse topology and energy management, or the Berkeley MAC utilize a queued wake-up where a threshold value is used to control the average time of switching on a node and the latency for buffered data packets. Determining the optimal value of the packet queue length of a node after which the node is switched on for transmission, is referred to as the N-policy. For more information see (Jiang et al., 2012).

Let d_i be the sum of the delays to data processing at node N_i and transmission from that node, and if data is generated at node N_i at the rate of λ_i, then we have

$$d_i = d\,(\lambda_i, P_i, K_i, T_i)\,, \quad \forall i, \tag{9}$$

and ω_i th power consumption at that node, given as

$$\omega_i = \omega\,(\lambda_i, P_i, K_i, T_i)\,, \quad \forall i. \tag{10}$$

Given the appropriate parameters of the system we can obtain the performance measures, whether we use single node queueing models or queueing network models.

3) Routing Aspects of WSN: Each sensor node needs to send its data (processed or unprocessed) to a sink node where decisions are taken for the whole system, especially for the IoT to be implementable. Apart from the usual link costs associated with networks in computing optimal routing paths for WSN we also need to know the energy level at each node. This aspect has to be incorporated in the routing algorithm keeping in mind that there is a need to preserve energy at nodes with low level of it. Hence routing here considers costs of links and nodes. One other tool that has been incorporated in routing for WSN is selection of cluster head node which is responsible for aggregating data from a group of nodes and then transmitting to the sink node (see Fig.6). This routing aspect for WSN is unique and has not received enough attention from the OR researchers. As the 5G technology is rolled out and the IoT developed to work using

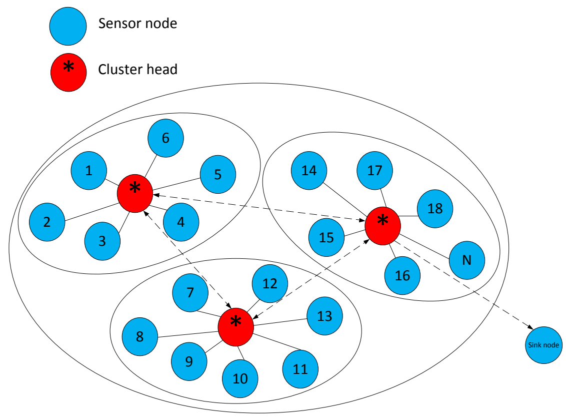

Figure 6: SSensor node distribution with cluster heads.

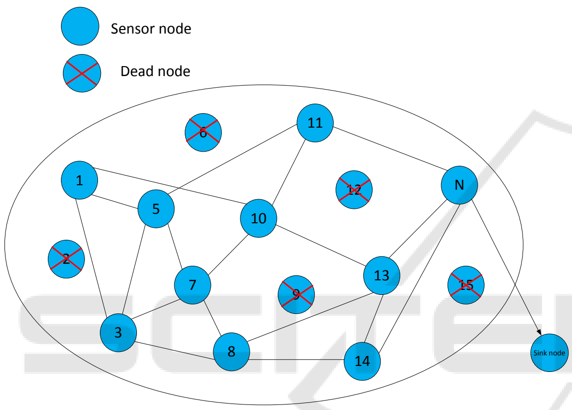

Figure 7: Sensor nodes in a depleting scenario.

that technology we want to maximize the technology to ensure high effectiveness and efficiency. This calls for the use of very effective and well researched OR tools.

4) Reliability of WSN: The reliability of the WSN is key to its effectiveness. It is important that if a sensor node is not in operation due to low power or faulty equipment, that data for the area can still be transmitted. So we need very good reliability model that assesses the impact of dead nodes as shown in Fig. 7.

SUGGESTED IDEA FOR COLLABORATION:
It is important that appropriate queueing models are developed for WSN in order to obtain more accurate estimate of delays at the nodes for the purpose of providing efficient performance. Oversimplified and inappropriate queueing models lead to gross overestimation or underestimation of performance measures leading to poor power management and inefficient routing. It is very common for telecommunication researchers to assume Poisson arrivals, when often the arrival process is far from that; and also ignoring correlations in the arrival process is very common in all the examples discussed in the last few sections. On the other hand, OR analysts tend to be very rigorous by developing general models that are more appropriate sometimes for unrealistic problems. Combining the rigour of OR analysts with the realistic view of the problems by telecommunication researchers would lead to a very appropriate and effective models. A good collaboration between the two professions where more realistic models are developed jointly and the effect of ignoring some aspects of the systems are well understood and accounted for would be the direction to go.

3.2 Sensor Node Placements

The placement of sensor nodes in a WSN is another major factor in the reliability of WSN and its lifetime. First in order for the WSN to be able to cover all areas of interest the selection of the node placements have to be selected strategically. For example, in (Cardei et al., 2005) the optimization problem is to maximize the number of set covers by selecting the optimal sensing range for each sensor in each set cover while ensuring each target is monitored by at least one sensor. This problem is referred to as the Adjustable Range Set Cover (AR-SC) problem and is initially formulated as the following integer linear program: Consider N sensor nodes $s_1, \ldots, s_N$ and M targets $t_1, t_2, \ldots, t_M$. Let the sensor have P sensing ranges $r_1, r_2, \ldots, r_P$ with corresponding energy consumption $e_1, e_2, \ldots, e_P$. If E is the initial sensor energy, and a_{ipj}, a binary coefficient which is 1 if sensor s_i with radius r_p covers the target t_j . Further let K be an upper bound for the number of set covers. Then we have the following decision variables:

Decision Variables:

c_k, boolean variable for $k = 1 \ldots K$, 1 if this subset is a set cover
x_{ikp}, boolean variable for $i = 1 \ldots N$, $k = 1 \ldots K$, $p = 1 \ldots P$, 1 if sensor i with range r_p is in cover k

The problem can now be set up as an integer linear program (ILP) as

ILP:

$$maximize \quad \sum_{i=k}^{K} c_k, \tag{11}$$

$$s.t. \quad \sum_{k=1}^{K} \left(\sum_{p=1}^{P} x_{ikp} e_p \right) \leq E \quad \forall i = 1 \ldots N, \tag{12}$$

$$\sum_{p=1}^{P} x_{ikp} \leq c_k \quad \forall i = 1\ldots N,\ k = 1\ldots K, \tag{13}$$

$$\sum_{i=1}^{N} \left(\sum_{p=1}^{P} x_{ikp} * a_{ipj} \right) \geq c_k \quad \forall k = 1\ldots K,\ j = 1\ldots M, \tag{14}$$

$$x_{ikp},\ c_k \in \{0,1\}. \tag{15}$$

In (Cardei et al., 2005) the integer constraint is relaxed to create a linear programming problem which is then used for the proposed LP based heuristic. The LP based heuristic uses the values for each variable obtained from solving the LP. The variables with nonzero values from each cover set are added to the new set in non-increasing order until all of the targets are covered. This was improved further by the authors in (Beynon and Alfa, 2015). If a sensor does not have sufficient energy for the suggested power level or does not cover any new targets it is not added to the set. If no more nonzero variables are left for the current cover and one or more targets remain uncovered then the set is not a cover set. After the maximum number of cover sets have been attempted to be made the solution is the set of all valid cover sets.

SUGGESTED IDEA FOR COLLABORATION:
One may argue that this type of problem has been well studied for years in OR as a class of problem in the family of maximum covering location problem. Yet telecommunication researchers still have unanswered questions about coming up with very good solutions for the maximum network lifetime in wireless sensor networks. Perhaps this is due to some subtleties in the later problem that are probably ignored in the classical OR versions of the problem. In our opinion this calls for more close collaborations between the two groups of researchers to understand the problem better and its associated issues.

3.3 IoT

The IoT is essentially driven by the automatic or "semi-automatic" control system. Data is sent from some form of sensors, e.g. WSN, and based on the data an action is taken as seen appropriate. For example, a sensor network that is monitoring the temperature at a building keeps gathering data and at each point may notice that the temperature is too high and thereby automatically control the system and lowers the temperature. This is one of the most elementary ones. Another simple example could be a case where as soon as a shopper in a grocery store is noticed by a sensor network in the store a message is sent to the shopper's home refrigerator sensors which then sends a message to the shopper's mobile phone to let him/her know they need more milk at home. The communication here is what is called device-to-device. However more important here is the need for a process that determines that the milk has reached low level or expired date etc and request the shopper to purchase some. This is close to an inventory model that is automated. The key difference is that there is a time factor involved. The shopper has to be able to get the message, from its mobile phone, when they are still in the store otherwise it is not very helpful. Hence latency is also a factor.

SUGGESTED IDEA FOR COLLABORATION:
This class of problem is more in the control domain and requires a good collaboration between both OR analysts and telecommunication researchers. It is still an evolving problem which can benefit early from the collaborations.

In the next section we give a brief example of another type of OR challenges for the future communication systems.

4 CONNECTING OPTIMIZATION OF CRN AND QUEUEING OF WSN

Currently WSN is operated on what is called the unlicensed channels. These channels are getting congested and it is being proposed that the licensed channels, which belong to PUs be used for transmitting data in WSN. The sensor nodes are like queueing nodes. Data is stored in the buffer and then transmitted when possible. The transmission will be carried out on licensed channels.

So here is the situation. Considering the PU channels, the SU, in this case the sensor node(s) will be assigned a capacity c_k^s on channel k from the optimization model for CRN in Section III. However, because the assigned capacity and the number of allocated channels are used by the SU to transmit the date the latency depends on this which should actually be incorporated as part of the optimization scheme in the CRN problem. How to capture this feedback is a major challenge. Here we present a possible example method for dealing with it.

Let M be the number of sensor nodes in the WSN, by trying to combine the two aspects then our Eq(1) in Section III will be

$$\max \quad z = \sum_{s=1}^{M} \left[\omega_s \sum_{k=1}^{K} c_k^s x_k^s - f(d_s) - g(\omega_s) \right], \quad (16)$$

where $f(d_s)$ is the cost of delay at sensor node s and $g(\omega_s)$ is the cost of power consumption at node s.

We will also have Eq(9) and Eq(10) as additional constraints for the optimization problem, in addition to stability sets of equations.

SUGGESTED IDEA FOR COLLABORATION: This will be a new and a bit more complex class of problems. If we decide to include the placement problem with this then the whole model becomes very challenging. The question of how to manage the problem should be of interest to OR analysts who traditionally have the expertise to handle them.

We suggest more close collaborations between OR analysts and Communication network researchers.

5 CONCLUSIONS & THE POSITION

We start by discussing the first example of cognitive radio networks. Given the information about channel capacity, which is usually stochastic, for SUs there are several research results for allocating that resource to the SUs using optimization tools. However, the allocations provide the service capacity to the users and hence a very good queueing model is needed to obtain the performance analysis, which itself will now feed back into the optimization tools. Hence what we need is a combined queueing and optimization model in order to efficiently model these systems.

Next we consider the wireless sensor networks, we see that the optimal placement of the sensor nodes determine network life, its reliability and routing which affects latency. The placements, routing and sleep/awake mode determines the queueing delays at the nodes which need to be included in the optimization component of the placements, etc. Hence for the WSN, combined optimization and queueing models are essential in order to have a well design WSN.

Finally, keeping in mind that an effective operation of IoT depends on accurately gathering information and passing it to the right destination within a very short time it is imperative that a combination of optimization and queueing models are needed for the planning.

In summary OR analysts and communication modelling researchers need to try and work very closely together in order to come up with efficient tools for analyzing modern day communication systems. That is the position that we are taking in this paper.

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