Designing Sustainable Smart Connected Communities using Dynamic Spectrum Access via Band Selection

Vijay K. Shah
Department of Computer Science
University of Kentucky, Lexington, USA
vijay.shah@uky.edu

Shameek Bhattacharjee
Department of Computer Science
Missouri University of Science and Technology, Rolla, USA
shameek@mst.edu

Simone Silvestri
Department of Computer Science
University of Kentucky, Lexington, USA
silvestri@cs.uky.edu

Sajal K. Das
Department of Computer Science
Missouri University of Science and Technology, Rolla, USA
sdas@mst.edu

ABSTRACT

While designing communication systems for *sustainable* smart connected communities (SCCs), particularly in rural or non-urban areas, *energy efficiency* is as important as quality of service (QoS). However, simultaneously satisfying both metrics is extremely challenging due to varying demands posed by heterogeneous sensing modalities, lack of dedicated infrastructure, and various sustainability constraints. While low-power short range technologies often fail to achieve high QoS, the use of 3GPP technologies e.g., LTE, LTE-A, GSM for connected communities will eventually face spectrum scarcity and cross technology interference. In this regards, *dynamic spectrum access* (DSA) offers a viable technology that overcomes policy constraints and improves spectrum scarcity by spectrum sharing. In this paper, we indeed show that harnessing DSA in the context of SCCs can achieve notable benefits in terms of energy efficiency. Specifically, we propose a novel architecture using a small scale DSA enabled overlay network over legacy infrastructure that improves end-to-end energy efficiency while guaranteeing QoS. The underlying idea is to selectively exploit distinct electro-magnetic characteristics of various bands with a goal to intelligently match any message requirement with a suitable band, and thus determine the optimal TTL constrained energy-efficient (TcE) path that enhances end-to-end energy efficiency and meets the TTL deadline. We formulate a constrained optimization problem and propose a dynamic programming approach for determining the optimal TcE path for any given message. Compared to the homogeneous band approaches that opportunistically access channels within a predetermined band, our study shows that the band selection approach improves energy efficiency by almost 40% while preserving QoS.

CCS CONCEPTS

•**Networks → Cognitive radios;** •**Hardware → Energy distribution; Impact on the environment;** *Sensor applications and deployments; Emerging technologies;* •**Computer systems organization →** *Embedded and cyber-physical systems;*

KEYWORDS

Dynamic Spectrum Access; Energy Efficiency; Sustainable Smart Communities; Band Selection; Green Communication; QoS

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1 INTRODUCTION

Ubiquitous connectivity is crucial for smart and connected communities (SCCs) – be it rural, sub-urban or urban. Such connectivity enables gathering, dissemination, and analysis of valuable information on multiple sensing modalities, for efficient decision making with a goal to improve quality and experience of human life [4]. To form such SCCs, huge *communication infrastructure* is needed to offload data from hundreds of physical *sensor blocks* to their respective decision making units (e.g., a data center or cloud) usually within certain time deadlines (a *QoS* metric). Such communities may be formed in both urban and non-urban areas. For example, a sensor block could be a remote rural farm equipped with moisture sensors, soil monitors, and wind sensors; or a smart home with temperature/light sensor, and smart meters; whose data need to be offloaded to a central utility for decision making.

However, realization of such huge communication infrastructure faces severe economic and sustainability challenges for both rural (non-urban) and urban areas. First, it is not cost-effective for providers to invest in dedicated infrastructure like base stations, access points with backhaul links, and spectrum licenses in non-urban areas due to low revenue returns compared to the high initial investment [15], [16]. Hence, sensor blocks planned in non-urban areas are usually far away from the data center or the nearest backhaul link. Second, while certain real-time latency critical decisions having a local area scope may use fog computing [3] (which requires dedicated infrastructure), many decisions need data over a wider area in the long run. Therefore, even in urban areas, the data need to travel larger distances between the data center and the sensor blocks. Even if the existence of infrastructure is assumed (as

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in urban areas), sending the collected data from large numbers of sensor blocks are likely to burden the existing wired networks and in turn require deployment of more routers and switches, which would require additional power and hence, exacerbates the problem of energy sustainability.

To address the above challenges related to communication infrastructure costs in non-urban areas and burdening the wired network in urban areas, SCCs could be realized through a network of fixed (or mobile) cyber-physical systems (e.g., road side units or RSUs, private smart vehicles, public transport) connected via wireless links [7], [8], without additional dedicated infrastructures. Such an option is feasible for decision making in SCCs that *do not* have very short real-time deadlines (termed as time-to-live, or TTL), such as rural smart homes constituting smart meters and indoor air quality or humidity sensors. As an example, smart meter data usually have one hour TTL for billing cycle whereas other basic sensor data may tolerate higher time delays, like 5-6 hours. Some generic ideas pertaining to such a possibility has been discussed in [4]. Thus, wireless spectrum becomes a critical resource for the success of SCCs in both non-urban and urban communities.

Current wireless technologies for SCCs typically include (i) Low Power Short Range (e.g. ZigBee, Bluetooth, WiFi, Low6PAN using 2.4 GHz) and (ii) 3GPP Standards (e.g., LTE, GSM, LTE-A using 1700-2100, 900 MHz). Low power technologies, although seemingly energy-efficient, have limited transmission coverage [6]. Since the data often travel larger distance, a large number of devices need to be deployed to form a multi-hop network [10] to guarantee a high QoS (i.e., data offloading within TTL deadline). However, such a communication network exacerbates the problem of both energy efficiency and infrastructure cost.

On the other hand, although 3GPP technologies (dominant in urban areas) provide higher transmission coverage, they incur higher energy expenditure [13] due to two major reasons. First, the coexistence of increasingly myriad devices in the same spectrum will cause cross technology interference, thus negatively impacting the signal-to-noise ratio (SINR) requirement. Therefore, either increased power or more re-transmissions would be required (see Sec 4). Second, the homogeneity of legacy spectrum access policy does not provide the flexibility to handle data traffic with heterogeneous demands (e.g., varying message sizes or TTL deadlines) that may be generated from the same sensor block. Such homogeneity of the spectrum access plan triggers the disadvantage of resource *over-provisioning* or *under-provisioning*, which again negatively impacts the achievable energy efficiency (see Sec 4).

In the last decade, Dynamic Spectrum Access (DSA) [5] has emerged as an attractive enabling paradigm that allows certain wireless devices to opportunistically switch and access two or more unoccupied bands (called *whitespaces* and grayspaces) originally licensed for other services on the condition of non-interference to the primary licensees or users. This provides an option to break away from the homogeneity of legacy spectrum access without the provider having to buy a fixed spectrum license. Empty channels within each band are liable to be selected for the actual communication. Till date, whitespace and grayspace networking has been allowed by policy in TV Band [23] [24], GSM Band [16], LTE Band [26], and Citizen Broadband Radio Service (CBRS) Band [1]. While the original purpose of DSA was to improve spectrum efficiency [12] and reduce cross technology interference, the fact that it allows switching among different bands could be used to improve the overall energy efficiency by opportunistically matching the electro-magnetic (EM) properties of each band with different sensing modalities' requirements. To this end, a decade long body of DSA research focused on interference free channel assignment given a particular band [27] [28], most of the energy efficiency research has been limited to efficient channel sensing approaches only [29]. However, with wide band spectrum analyzers and the notion of spectrum access systems (that coordinates spectrum assignments) [33] becoming increasing available, in near future a DSA end node is expected to have multiple choices for band selection.

In this paper, we show that apart from other factors, the band type is an important factor that affects the network energy efficiency given the varying message and QoS requirements. First, we propose an energy-efficient communication architecture for SCCs using a small number of DSA enabled devices that form an overlay network on top of the legacy infrastructure. The proposed approach exploits the distinct electro-magnetic (EM) characteristics of different bands in order to intelligently match any message requirement to a suitable band and, hence determines an optimal TTL constrained energy-efficient (TcE) path that achieves the best end-to-end energy efficiency and meets the TTL deadline. We formulate a constrained optimization problem for the determination of TcE path for any given message requirement. We also propose a polynomial-time dynamic programming approach for solving the optimization problem where the DSA overlay topology is relatively steady. Compared to the homogeneous band access and spectrum sharing approaches that are restricted to opportunistically access an available channel within a predetermined band, we show that the proposed approach utilizing band selection significantly improves the energy efficiency by almost 40% while preserving the QoS. Finally, we investigate some challenges of band selection for a variable overlay topology without global knowledge as a case study. To the best of our knowledge, no prior work investigated the energy efficient communication through suitable band selection for various message requirements. The benefit of this work is that it provides an easy-to-deploy and low cost option to connect non-urban communities with improved energy efficiency. Moreover, it provides an alternative for improved energy-efficient communication network without burdening the wired infrastructures or incurring any additional cost, for urban communities.

The rest of the paper is organized as follows. Section 2 reviews the related work and Section 3 presents the proposed DSA enabled overlay architecture for SCCs. Section 4 discusses the distinct EM characteristics of various bands that can be exploited to achieve energy-efficiency. Section 5 presents the proposed band selection approach for a steady DSA topology. Section 6 presents the simulation results, while Section 7 discusses challenges and roadmap for band selection under variable DSA topology. Finally, Section 8 concludes the paper.

2 RELATED WORK

We review the related literature for both traditional (non-DSA) and DSA/spectrum sharing approaches for smart connected communities using wireless cyber-physical systems. Several non-DSA wireless communication systems (e.g. DakNet [17], KioskNet [18]) have been proposed to provide connectivity by utilizing buses and public service vehicles (equipped with computers and Wi-Fi radio) as mechanical backhaul that provides internet connectivity to rural or remote communities. In contrast, JaldiMAC [20] utilized long-range directional WiFi to form a wireless mesh network for providing connectivity in sparsely populated areas. In [19], the deployment of low power GSM based Village Base Station (VBTS) was proposed for rural telephony. In [21] and [22], the authors proposed connectivity utilizing hand-held wireless devices for transient conditions. Google [25] introduced the network of balloons traveling on the edge of space, designed to extend Internet connectivity to people in rural and remote areas. However, these approaches utilize standard wireless technologies, such as WiFi, WiMax, GSM base station, VSAT, WLAN, wireless mesh, or a combination of them, in order to provide connectivity to the rural communities. Since all these devices access a homogeneous band (usually ISM or LTE), they suffer from limited coverage, under-provisioning, over-provisioning, and policy constraints as discussed later. Finally, 3GPP/GSM technology providers are also less motivated to invest in expensive wireless spectrum licenses even after government subsidies in developing countries [16].

Recently, the researchers have proposed the utilization of TV whitespaces [23], [24] and GSM whitespaces [16] for rural connectivity. These approaches allow the secondary devices to dynamically utilize the whitespaces in fixed band (e.g., TV, GSM) for data communication. Some researchers [11] have also proposed cognitive wireless sensor network (CWSN) where each sensor harnesses DSA for energy-efficiency. However, the CWSN approach is impractical for community scale deployments for it requires every sensor node to be DSA enabled, which is costly. Additionally, these works do not discuss what band type is utilized. We show in the paper that restricting the SCC to one such band is not optimally energy-efficient.

3 PROPOSED ARCHITECTURE

This section presents key components, network model and communication mechanism for the proposed DSA overlay architecture.

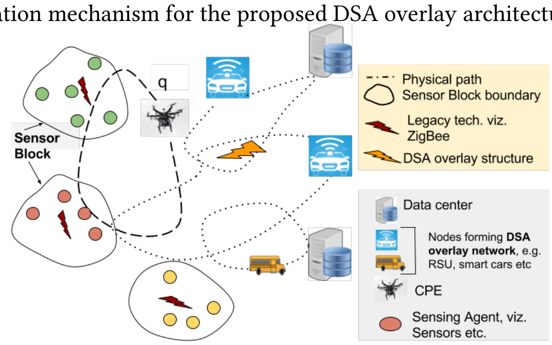


Figure 1: Proposed Architecture

3.1 Key Components

Sensor Blocks : A sensor block is a small physical sub network (such as a smart building, a crop field etc.) constituting heterogeneous *sensing agents*. A sensing agent could be a sensor or a smart device that collects different sensory or contextual data including, texts, images, audio, video, etc. Such data may have different sizes, ranging from few Kbs (e.g., text) to several Mbs (e.g., images, videos) and varying TTL deadlines of few hours (non-real time). As an example, a rural smart home may constitute temperature/light sensors and smart meter. Recall a smart meter data usually have 1 hour TTL for billing cycle whereas a sensor data on pollution levels, moisture, etc. may have a larger deadline upto 5-6 hours. Therefore, each sensor block can be a source of various data, each with heterogeneous demands. Owing to the smaller size of the sensor block, it can be assumed that the sensing agents within each block form a multi-hop ad-hoc network of low-power short range legacy technologies that forwards its messages to a visiting *consumer premise equipment* [14]. Unlike previous works [11], our work does not require the sensing agents to be DSA enabled, thereby making it practical and cost-effective.

Consumer Premise Equipment (CPE) : A CPE acts as a proxy between the sensor blocks and the DSA overlay network (explained below). A CPE could be a flying drone or a moving vehicle, that *periodically* collects various messages from a predetermined set of sensor blocks (denoted by $q \in Q$, where Q is the set of CPEs). This obviates the need for a dedicated infrastructure, such as separate access points or DSA enabled sensing agents, at each sensor block. We consider that each CPE has two wireless interfaces– a low-power short range interface and a DSA interface to communicate with the sensor blocks and other DSA enabled devices, respectively.

Data Center : A data center is a base station with a back haul link to the final decision making unit, where all the generated messages need to be delivered for the computation and analysis. Each member in the set of data centers (denoted by C) has DSA capability.

DSA Overlay Network : The DSA overlay network is a collection of DSA enabled devices that acts as a bridge between the CPEs and the data center. For example, fixed road side assistance units (RSU) [9], connected public transportation, smart vehicles, etc. Such a set of DSA enabled devices (denoted by R) form a wireless DSA overlay network, where each DSA enabled device opportunistically accesses an unoccupied channel on a suitable band for communication. We refrain from discussing the details of the mechanisms used for the discovery and selection of unoccupied (non-interfered) channel within a given band because such issues have been extensively studied in the literature [5], [27], [28].

We assume that there exists a set S of bands where each band $s \in S$ has several (sub) channels. We have considered $S = \{\text{TV, LTE, ISM, CBRS}\}$, however, it can be easily extended to any other unlicensed or licensed bands where DSA is allowed. For example, millimeter bands ($30 - 300$ GHz) are being discussed for communication in future 5G technologies [31], [32]. The details of operating frequencies for these bands are shown in Table 1. Hereafter, a *node* denotes a DSA enabled device.

While the DSA network topology could be of two types, the focus of this paper is the first one. The types are:

Steady network topology : In this case, the overlay nodes are either fixed (i.e., RSUs) or have predictable mobility trajectories (such as public buses, municipal vehicles). Each node shares its trajectory and spectrum availability information with other nodes in the network via a dedicated *common control channel* or other synchronization techniques as discussed in the recent DSA standards [1], [2]. These mechanisms make it possible for each node to possess *global knowledge* about the *approximate geographical location* and *spectrum availability* at every other node.

Variable network topology : In this case, the DSA overlay nodes may have variable (unpredictable) mobility pattern (e.g. a private vehicle). Hence, a node cannot possess accurate global knowledge of the network. However it may gather the *local knowledge* about the neighboring nodes via the common control channel.

3.2 Network Model

We model the DSA overlay network topology as a directed graph (see Fig. 3) $G = (V, S, E)$ where $V = Q \cup C \cup R$ is the set of all nodes i.e., CPEs, data centers and intermediate nodes, respectively; S is the set of band types; and $E \subseteq (V \times V \times S)$ is the set of all directed links between any two nodes over common (free) channel in any band type. $e_{ij}^{(s)} \in E$ is a directed link from node i to node j over a band $s \in S$. Hence, there may exist atmost $|S|$ unique links between any given node pair $i, j \in V$. We denote any message in G by $m < u, v, L, T >$ where u is the source, v is the destination, L is the message size, and T is the TTL deadline. Now, for a given message m, each link over band s is characterized by a tuple $< w_{ij}^{(s)}(L), \hat{t}_{ij}^{(s)}(L) >$, denoting the energy and latency costs, respectively.

3.3 Communication Mechanism

As shown in Fig. 2, a CPE $q \in Q$ periodically broadcasts a *Hello* packet in the predetermined sensor blocks. On receiving the *Hello* packets, every sensing agent in a sensor block switches from a default energy-saving *Sleep* (receive only) mode to an *Active* (transmit and receive) mode, and transmits the messages directly or indirectly via other sensing agents to the CPE q. The CPE, then broadcasts the *Sleep* packet in the sensor block such that the sensing agents switch back to the energy-saving *Sleep* mode. Meanwhile, the CPE selects a suitable energy-efficient band (say, $s \in S$). We discuss the band selection approach in Sections 5 and 7 for steady and variable DSA overlay topologies, respectively.

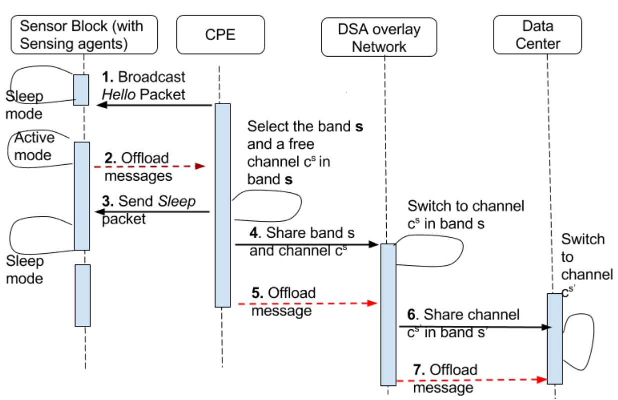


Figure 2: Communication Mechanism

Once the band s is determined, the CPE q shares the chosen band and the channel information (denoted by $c^{(s)}$) with any node in the DSA overlay network (or the data center if in range), which then switches to the channel $c^{(s)}$ in the chosen band type s. Note that a unique node is determined in the steady topology whereas in case of variable topology, the CPE q floods the information to every neighboring node to improve the chances of message delivery. After that, q transmits the stored messages to the chosen node(s) in the DSA overlay network (or data center if in range) over channel $c^{(s)}$. The similar process continues at each intermediate node in the path from the CPE to the intended data center.

To meet the objective of this work (i.e., end-to-end energy efficiency while not sacrificing the QoS), any message $m < u, v, L, T >$ from a node u (e.g., CPE) has to be delivered to the data center v in an energy-efficient manner while guaranteeing the TTL deadline. Therefore, in the rest of the paper, we primarily investigate the determination of *TTL constrained energy-efficient* (TcE) path, $p(u, v)$ through optimal band selection for any given message m such that the end-to-end energy efficiency is maximized and the TTL deadline is met.

4 TRADE-OFFS BETWEEN BAND SELECTION AND ENERGY EFFICIENCY

In this section, we first present the energy consumption model for DSA overlay network. Then, we discuss how unique electromagnetic characteristics offered by various bands can be intelligently exploited to improve the energy efficiency of the DSA overlay network for SCCs.

4.1 Energy Consumption Model

For DSA overlay network graph G, let a source node u transmits a message $m < u, v, L, T >$ to the destination node v, which is d_{uv} Euclidean distance apart. Suppose, $P_i^{(s)}$ is the transmit power at any node i over band s and $\gamma^{(s)}$ is the transmission coverage achieved over a band s. Let $\mathbb{R}_{ij}^{(s)}$ be the effective bit rate achieved from node i to node j over the band s. Recall that different bands have different electro-magnetic (EM) characteristics that may result in different allowable transmit power, coverage and effective bit rates (explained later in this section).

Since the DSA overlay network is influenced by various EM factors, such as operational frequency, bandwidth, path loss factor, and interference, the energy consumption model must consider all these factors. Now, given a path $p(u, v)$ for the message m, the end-to-end energy consumption is given by:

$$w_{uv}(L) = \sum_{e_{ij}^{(s)} \in p(u,v)} w_{ij}^{s}(L) = \sum_{e_{ij}^{(s)} \in p(u,v)} P_i^{(s)} \times t_{ij}^{(s)}(L) \quad (1)$$

where $e_{ij}^{(s)}$ denotes an intermediate edge on path $p(u, v)$. The *message transmission time* $\left(t_{ij}^{(s)}(L) = \frac{L}{\mathbb{R}_{ij}^{(s)}}\right)$, defined as the time taken to deliver the entire message m from node i to node j over a band s i.e., along the edge $e_{ij}^{(s)}$ as explained in Section 4.3). Now, considering that every node is restricted to utilize the same band, termed the *homogeneous band access* then, $w_{uv}(L)$ is given by

$$w_{uv}(L) = P_u^{(s)} \times t_{ij}^{(s)}(L) \times H \quad (2)$$

H is the number of hops required to transfer the message from node u to node v, calculated as $H = \frac{d_{uv}}{\gamma^{(s)}}$.

4.2 Operating Frequency and Energy Efficiency

We know that the received signal strength at a receiver should meet some reception threshold τ to decode a signal accurately. The generalized Frii's transmission equation provides the relationship between the received power at receiver j and transmit power from transmitter i over any channel with a representative frequency [1] $f^{(s)}$ in band s,

$$P_j^{(s)} = P_i^{(s)} G_i G_j \left(\frac{\mathbb{C}}{4\pi f^{(s)} d} \right)^{\alpha} \geq \tau \quad (3)$$

where, G_i and G_j are the transmitter and receiver antenna gains, α is path loss exponent, $\mathbb{C}$ is the speed of light, d is the distance between i and j, $P_i^{(s)}$ is the transmit power of i, and $P_j^{(s)}$ is the received power at j. Now $\phi = G_i G_j (\frac{\mathbb{C}}{4\pi})^{\alpha}$ be a constant.

Then, from $P_j^{(s)} = \phi \frac{P_i^{(s)}}{(f^{(s)}d)^{\alpha}}$, it is evident that for higher frequencies, the transmit power $P_i^{(s)}$ ought to be increased to maintain the same power above the threshold, i.e., $P_j^{(s)} \geq \tau$, even though the distance d is unchanged. The resultant increased transmit power requires more energy consumption (refer to Eqs. 1 and 2). Alternatively, if the transmit power is not increased, then τ is only met at a lower distance. Hence, more intermediate hops would be required to traverse the same distance d, leading to the additional transmission and reception operations at each intermediate hop which causes higher energy expenditure.

Moreover, the lower frequencies have larger wavelengths yielding better obstacle and wall penetration capabilities. Hence, the lower frequencies are less error prone, thus reducing (re) transmission overheads and enabling better non line-of-sight connectivity. Among the bands that allow DSA, TV and LTE bands have lower frequency allocations than traditionally used unlicensed band (2.4 GHz). Hence, these bands should be more energy efficient.

However, lower frequencies come at a trade-off in the sense that they usually have much lesser bandwidth of 6 MHz as opposed to LTE (upto 20 MHz), and CBRS (upto 40 MHz). Thus, for larger message sizes, the message transmission time (refer to Eq. 6) will be higher. Alongside, supporting high data rate applications are also challenging for lower frequencies offering smaller bandwidths. However, frequencies offering higher bandwidths will reduce the transmission time for a given message size and save energy. An important research question, therefore, is that whether the reduction in the transmission time for higher frequencies offsets the gain in energy efficiency due to reduced hop count.

4.3 Bandwidth and Energy Efficiency

The relationship between bandwidth and dissipated power could be understood through Rayleigh-Parseval Equation:

$$P_{dis}^{(s)} = \int_{f_1^{(s)}}^{f_2^{(s)}} \mathbb{S}_i(f^{(s)}) df \quad (4)$$

where $\mathbb{S}_i$ is the power spectral density, $\Delta f^{(s)} = (f_2^{(s)} - f_1^{(s)})$ is the bandwidth of any channel in the band type s and $P_{req}^{(s)}$ is the total power dissipated over band s. From Eq. 4, it is clear that a channel offering higher bandwidth causes larger power dissipation. Given a fixed transmission time for any message, higher bandwidth channels will consume more energy than the lower ones. The typical bandwidths for various spectrum is listed in Table 1.

On contrary, from Shannon-Hartley theorem, the effective bit rate ($\mathbb{R}_{ij}^{(s)}$) between transmitter i and receiver j over any channel in band s with representative frequency $f^{(s)}$ is given by:

[1] For example, $f_s = 2.4$ GHz for the frequencies in the range 2.412 - 2.462 GHz used by legacy WiFi devices in ISM Band

Table 1: Spectrum profile

Spectrum	Bandwidth
54-216 MHz (VHF TV Band)	6MHz
470-698 MHz (UHF TV Band)	6MHz
698-806 MHz (700 MHz Band/FirstNet)	6 MHz
700-800 MHz/1700-2100 MHz (LTE Band)	5 - 20 MHz
902 - 928 MHz (ISM Band)	3-8 MHz
2.4 - 2.5 GHz (ISM Band)	2 - 50 MHz
3.5 - 3.7 GHz (CBRS Band)	10 - 40 MHz
5.7 - 5.8 GHz (ISM Band)	20 - 80 MHz

$$\mathbb{R}_{ij}^{(s)} = B^{(s)} log_2 \left(1 + \chi_{ij}^{(s)}\right) = B^{(s)} log_2 \left(1 + \phi \frac{P_i^{(s)}}{(f^{(s)}d)^{\alpha} N^{(s)}}\right) \quad (5)$$

where $B^{(s)}$ is the bandwidth of any channel in band type s and $\chi_{ij}^{(s)} = P_j^{(s)}/N^{(s)}$ is the ratio of the communication signal power to the interference and noise (SINR) at the receiver. The rest of the notations are the same as before.

For a given fixed message of L bits, the total transmission time is calculated as follows:

$$t_{ij}^{(s)}(L) = \frac{L}{\mathbb{R}_{ij}^{(s)}} = \frac{L}{B^{(s)} log_2 \left(1 + \phi \frac{P_i^{(s)}}{(f^{(s)}d)^{\alpha} N^{(s)}}\right)} \quad (6)$$

From Eq. 5, given that the SINR is unchanged, a higher bandwidth channel would offer a higher effective bit rate, thereby decreasing the required transmission time.

Hence, from the relationship between bandwidth and required power (Eq. 4) and effective bit rate (Eq. 5), the higher the channel bandwidth, the higher is the dissipated power but the lower is the transmission time. Thus, the trade-off is whether to choose a high bandwidth channel that reduces the transmission time and increases the dissipated power or vice-versa for any given message.

4.4 Interference and Energy Efficiency

Increased cross device interference will increase the noise floor as more and more devices coexist in the unlicensed spectrum (2.4 GHz) and GSM/LTE (1700-2100 MHz) band. Therefore, from Eq. 5, it is evident that SINR will decrease. To maintain a certain required SINR, the transmit power needs to be increased. However, switching to any other band type using DSA would allow to maintain the same SINR with a low transmit power, thus saving energy.

4.5 Packet Size and Energy Efficiency

Packet sizes in existing low-power short range technologies (2.4 GHz) are usually small (maximum size 128 bytes) because the bit error rate is very high. However, communication through lower frequency bands experiences smaller bit error rate (as explained in Section 4.2). Hence, larger packet sizes can be employed to reduce per-packet overheads such as headers and preambles, as shown in [13]. Moreover, the higher packet size would decrease the overall message transmission time. Both these factors promises to improve the energy-efficiency.

5 BAND SELECTION WITH GLOBAL KNOWLEDGE

In this section, we discuss the proposed *band selection* approach for steady network topology where each node has the global knowledge of the network. The main idea is to intelligently match the message $m < u, v, L, T >$ to a suitable band at each intermediate node between the source u and destination v so as to construct the TTL constrained energy-efficient (TcE) path $p(u, v)$. We first show that the greedy approaches for band selection do not always achieve best energy-efficient path, $p(u, v)$ that also meets the TTL deadline (i.e., optimal TcE path) for any given message.

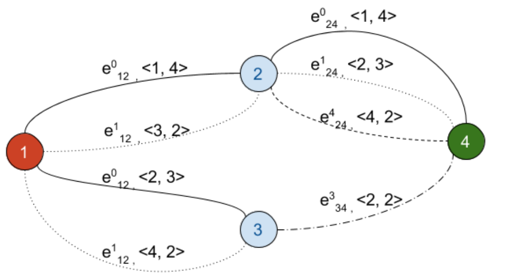


Figure 3: Network Model. e^0_{12} and e^1_{12} denote links between nodes 1 and 2 over band type 0 and 1, respectively. Tuples $< 1, 4 >$ and $< 3, 2 >$ signify energy and latency costs across links e^0_{12} and e^1_{12}, respectively.

Claim 1: *Any path $p'(u, v)$, which is constructed by selecting optimal (i.e., energy-efficient) band locally, among available bands at each intermediate node, may not always yield the optimal TcE path $p(u, v)$ for any given message $m < u, v, L, T >$.*

Proof: Let us consider the network (depicted in Fig. 3) where nodes 1 and 4 are the source and destination, respectively, and a message m with TTL deadline $T = 5$, initially at node 1. Then, the path constructed by choosing locally optimal band at each intermediate node $p'(1, 4)$ would be

$$1 \xrightarrow[\text{Band } 0]{e^0_{12},\ <1,4>} 2 \not\rightarrow\ 4$$

There exists no solution i.e., optimal TcE path $p'(1, 4)$ that meets the TTL, $T = 5$. Here, the optimal TcE path $p(1, 4)$ is as follows:

$$1 \xrightarrow[\text{Band } 0]{e^0_{12},\ <2,3>} 3 \xrightarrow[\text{Band } 3]{e^3_{34},\ <2,2>} 4$$

Hence, the greedy approach of selecting optimal band at each intermediate node locally, do not always guarantee the construction of optimal TcE path for any message.

Claim 2: *Any path $p'(u, v)$, which is constructed by selecting the optimal (or energy-efficient) unique homogeneous band at each intermediate node, may not always yield the optimal TcE path $p(u, v)$ for any message $m < u, v, L, T >$.*

Proof: It can be proved easily as before (from above example network as shown in Fig. 3).

We present and prove these claims to show that the construction of optimal TcE path for any given message is not straightforward. None of the above greedy approaches can always guarantee the construction of optimal TcE path. Hence, we formulate the following optimization problem and propose a dynamic programming approach to find the optimal solution in polynomial time.

5.1 Problem Formulation

This section formulates a *constrained optimization problem* where the objective is to determine the TTL constrained energy-efficient (TcE) path for any message $m < u, v, L, T >$.

Although we solve the optimization problem for a given message m, it will also work well for concurrent messages. This is because a band is composed of several channels, that can be simultaneously accessed by concurrent messages (should they end up choosing the same band in the same geographical region); unless in the unlikely event that the number of such messages exceeds the total number of available channels. Moreover, there may be a small channel access delay due to channel bargaining within a selected band, which is negligible in the range of micro seconds; therefore the optimization problem ignores it.

The determination of an energy-efficient path for a message $m < u, v, L, T >$ can now be formally defined as follows: Given a directed graph $G = (V, S, E)$, an energy cost $w^{(s)}_{ij}(L)$ and a latency cost $\hat{t}^{(s)}_{ij}(L)$ to transmit a message $m < u, v, L, T >$ along a link $e^{(s)}_{ij} \in E$, a source node $u \in V$, a destination $v \in V$, the optimization problem is:

$$\min_{p(u,v) \in P'(u,v)} \sum_{e^{(s)}_{ij} \in p(u,v)} w^{(s)}_{i,j}(L) \tag{7}$$

where $P'(u, v) \subseteq P(u, v)$ is the set of all paths from the source node u to the destination node v which meets the constraints:

(i) SINR constraint : For the successful decoding of any message m at j, the achieved SINR $\chi^{(s)}_{ij}$ at receiver j must be greater than or equal to the prespecified SINR threshold χ_{th}.

$$\chi^{(s)}_{ij} \geq \chi_{th} \tag{8}$$

(ii) Power constraint : As per the FCC guidelines, the maximum transmit power at any transmitter i must be less than or equal to a fixed value, the maximum EIRP (effective isotropically radiated power) $P^{(s)}_{max}$ over any band $s \in S$.

$$P^{(s)}_i \leq P^{(s)}_{max} \tag{9}$$

(iii) Transmission coverage constraint : For successful data communication over any intermediate link $e^{(s)}_{ij} \in p$, the Euclidean distance d_{ij} must be less than or equal to the transmission coverage $\gamma^{(s)}$ achieved in the chosen band s.

$$\gamma^{(s)} \geq d_{ij} \tag{10}$$

(iv) Unique spectrum constraint : Any transmitter-receiver node pair $i, j \in V$ must tune to a common available channel in a unique band $s \in S$.

$$\sum_{s \in S} e^{(s)}_{ij} \leq 1, \qquad \forall e^{(s)}_{ij} \in p \tag{11}$$

(v) TTL constraint : Any message must be delivered within its time-to-live (TTL) from its source node u to destination node v. Hence the total latency cost $\left(\sum_{e^{(s)}_{ij} \in p(u,v)} \hat{t}^{(s)}_{ij}(L) \right)$ for the chosen path, i.e., the message transmission delay ($t^{(s)}_{ij} = L/\mathbb{R}^s_{ij}$) (first part) and propagation delay ($d_{ij}/\mathbb{C}$) (second part) and queuing delay (ϵ), must be less than or equal to the TTL bound T, shown as follows.

$$\sum_{e^{(s)}_{ij} \in p(u,v)} \frac{L}{\mathbb{R}^{(s)}_{ij}} + \frac{d_{ij}}{\mathbb{C}} + \epsilon \leq T \tag{12}$$

where $\mathbb{C}$ is the spectrum propagation speed(usually speed of the light). Note that the propagation and queuing delays are usually *negligible* compared to the message transmission delay.

5.2 Proposed TcE Algorithm

We propose a dynamic programming (DP) approach for the above constrained optimization problem. The proposed algorithm intelligently matches the message m to an optimal (energy-efficient) band such that the total energy cost incurred along path $p(u, v)$ is minimized whereas the TTL and other constraints are met. The proposed TcE algorithm is inspired from the well-known Floyd-Warshall algorithm for all pair shortest path algorithm.

Now, for a message m with L bits and TTL deadline, T at each source node $i \in V$ over band $s \in S$, the graph $G = (V, S, E)$ can be represented by a three-dimensional adjacency matrix $A : |V| \times |V| \times |S|$, defined as follows:

$$A[i,j,s] = \begin{cases} < 0, 0 >, & i = j \\ < w_{ij}^{(s)}(L), t_{ij}^{(s)}(L) >, & i \neq j, \text{ and constraints} \\ & \text{in Eqs. 8, 9, 10, and 11 are met} \\ < \infty, \infty > & \text{otherwise} \end{cases} \quad (13)$$

An element in $A[i, j, s]$ is an ordered pair $< ., . >$ where the first and second parts denote the energy and latency costs, respectively for a message m along the link e_{ij}^{s} from node i to node j over band s. The TcE algorithm is based on the notion of *intermediate node*, which is defined as follows.

Definition 1 (Intermediate node): Given a path $p =< 1, 2, ..., (|l|-1), |l| >$, an intermediate node is any node i such that $i = 2, ..., (|l|-1)$, i.e., any node except 1 and $|l|$.

The TcE algorithm is based on the following observation. Let us consider a subset of nodes $\{1, \ldots k\}$. For any node pair $i, j \in V$, let p be the path with least energy cost, among all paths between i and j whose intermediate nodes are in $\{1, \ldots k\}$. There are two possible cases.

k is not an intermediate node of p : all the intermediate nodes of path p are in $\{1, \ldots, k-1\}$. Hence, the energy-efficient path from i to j with intermediate nodes $\{1, \ldots, k\}$ is also the energy-efficient path from i to j with intermediate nodes in $\{1, \ldots, k-1\}$.

k is an intermediate node of p : p can be broken into two sub-paths: one sub-path p_1 from i to k and another sub-path p_2 from k to j. Since p is energy-efficient path, k can only appear once in p. Therefore, k can not be an intermediate node of p_1 or p_2. Moreover, *by optimality principle (that states that the sub-paths of shortest path are also shortest paths)*, both p_1 and p_2 are the shortest, i.e., energy-efficient paths between i and k, and k and j, respectively, with intermediate nodes in the set $\{1, \ldots k-1\}$.

We define the sub problems used by the DP approach as follows. Let $w_{ij}^{(k,T)}$ be the energy cost of the energy-efficient path from node i to j that meets TTL, T and all the intermediate nodes are in the set $\{1, 2, ..., k\}$. Now, we utilize above observations to define the recursive relation between the solutions of sub-problems, and ultimately lead to the solution of the overall problem.

Base case:

1. $k = 0$, There are no intermediate nodes in the path, hence for each $i, j \in V$,

$$w_{ij}^{(0,T)} = \begin{cases} \min_{s \in S} A[i,j,s] \rightarrow w_{ij}^{(s)}(L), & if\ \exists s \in S \text{ s.t } \hat{t}_{ij}^{(s)} \leq T \\ \infty & \text{otherwise} \end{cases} \quad (14)$$

2. $T = 0$, there is no path, hence $w_{ij}^{(k,0)} = \infty$, for each $i, j \in V$.

Algorithm 1 Initialization

Input: Adjacency matrix (W), TcE path matrix (P)
Ouput: $W^{(0,T)}$, $P^{(0,T)}$
for $i = 0$ to $|V|$ **do**
  for $j = 0$ to $|V|$ **do**
    $minECost = \infty$, $isValidPath = false$
    for $t = 0$ to T **do**
      for $s = 0$ to $|S|$ **do**
        if $i == j$ **then**
          $W[i][j][t] = 0$, $P[i][j][t] = -1$
        if $i \neq j$ and $A[i][j][s] \rightarrow \hat{t}_{ij}^{(s)}(L) == t$ and $minECost > A[i][j][s] \rightarrow w_{ij}^{(s)}(L)$ **then**
          $isValidPath = true$
          $W[i][j][t] = A[i][j][s] \rightarrow w_{ij}^{(s)}(L)$
          $minECost = A[i][j][s] \rightarrow w_{ij}^{(s)}(L)$
          $P[i][j][t] = i$
      if $i \neq j$ and $isValidPath == false$ **then**
        $W[i][j][t] = \infty$
        $P[i][j][t] = -1$
      if $t > 0$ and $W[i][j][t] > W[i][j][t-1]$ **then**
        $W[i][j][t] = W[i][j][t-1]$
        $minECost = W[i][j][t-1]$
        $P[i][j][t] = i$

Inductive case, $k > 0$ and $T > 0$, we can select a path with the least energy cost either using k as an intermediate node or not, however meets the TTL deadline, T.

$$w_{ij}^{(k,T)} = \min_{t=1 \ldots T} \left(w_{ij}^{(k-1),t}, \min_{t_1=0 \ldots t} \left(w_{ik}^{(k-1),t_1} + w_{kj}^{(k-1),(t-t_1)} \right) \right)$$

When $k = |V|$ and $t = T$, then we have the final solution, which is the total energy cost for the energy-efficient path for each pair of source-destination node pair with deadline T, i.e., $W^{(|V|,T)} = (w_{ij}^{(|V|,T)})$ for all $i, j \in V$.

Algorithm 2 TcE Path via Optimal Band Selection

Input: Adjacency matrix W
Ouput: TcE path $p(i, j)$ and optimal energy cost $w_{ij}^{(|V|,T)}$ $\forall\ i, j \in V$
procedure TcE()
  $W^{(0,T)}$ = initializeAdjacencyMatrix(W)
  //Determine TTL constrained energy-efficient path for each node pair $i, j \in V$
  for $k = 0$ to $|V|$ **do**
    for $t = 0$ to T **do**
      for $i = 0$ to $|V|$ **do**
        for $j = 0$ to $|V|$ **do**
          for $t_1 = 0$ to t **do**
            if $W[i][j][t] > W[i][k][t_1] + W[k][j][t-t_1]$ **then**
              $W[i][j][t] = W[i][k][t_1] + W[k][j][t-t_1]$
              $P[i][j][t] = P[k][j][t-t1]$
  Recursively navigate $P[i][j][T]$ to get the optimal path $p(i, j)$ with TTL deadline T.

Algorithm Description: The TcE algorithm uses a series of three-dimensional matrices $W^{(k,t)}$ for $k = 0, \ldots |V|$ and $t = 0, \ldots T$. Note $W^{(k,t)}$ contains the elements $w_{ij}^{(k,t)}$, that is the TTL ($1 \leq t \leq T$) constrained energy-efficient path between i and j using the intermediate nodes in $\{1, \ldots k\}$. Also, we keep track of the optimal TcE path in another matrix $P_{ij}^{(k,t)}$. The TcE algorithm has two steps: Step 1 (Initialization): The TcE algorithm first initializes the matrix $W^{(0,T)}$ to A under the following conditions (depicted in Algorithm 1). It also initializes TcE path tracking matrix, $P^{(0,T)}$ (Lines 8 - 21).

$$w_{ij}^{(0,t)} = \begin{cases} 0 \text{ if } & i == j \\ min\big(w_{ij}^{(0,t-1)}, \min_{s \in S}(A[i,j,s] \rightarrow w_{ij}^{(s)}(L))\big) \\ & \text{if } i \neq j \text{ and } A[i,j,s] \rightarrow \hat{t}_{ij}^{(s)}(L) == t \\ \infty & otherwise \end{cases} \tag{15}$$

Step 2 (TcE path via band selection): After the initialization (i.e., Step 1), the TcE algorithm applies the recursive formula to calculate $W^{(k,t)}$ given $W^{(k-1,t_1)}$ and $W^{(k-1,t-t_1)}$ where $1 \leq t_1 \leq t$, as shown in Algorithm 2. Also, the path tracking matrix P is updated recursively (Lines 6 - 13).

Finally, any source node i delivers the message to the intended destination node j via the computed optimal TcE path $p(i,j)$ obtained from path tracking matrix P. The total time complexity of the TcE algorithm is $O(|V|^3 \times T^2)$ where $|V|$ is the number of nodes, and T is the message TTL deadline.

5.3 Discussion on Cost Benefit Analysis

Many detractors of sustainability argue that green computing incurs higher capital expenditure and operational cost which drains the economy/revenue and makes such designs infeasible in practice. However, we believe that our proposed approach of opportunistic band selection to realize SCCs, is free from most such disadvantages due to the following reasons: (i) The use of DSA enabled access does not require a SCC provider to own dedicated spectrum licenses, worth millions of dollars regardless of variable traffic volume; (ii) Multiple smart communities can be connected with a small set of DSA overlay nodes where each DSA node average cost is roughly around \$500-\$700. In contrast, our design obviates the need for new dedicated infrastructure such as cellular base station (\$200,000/station) [30] in rural areas, and the need for extensive wire line communications to increase the available bandwidth in urban areas. Also burdening the existing networks, whether wired or wireless is obviated; and (iii) Some real examples of micro-telco models of DSA based deployment has already taken place in relatively rural areas in the developing world such as Papua [16], South Africa [34], Mexico [35], and Philippines [36].

To summarize, there is sufficient practical evidence to suggest that the equipment and operational costs are far less compared to the traditional approaches. The major hurdles are the policy issues which surround spectrum planning. However, significant breakthroughs [1], [2] in spectrum policy have been made in recent years and DSA enabled devices mounted over drones, smart public transport [7], and private smart cars [8] are going to be a reality.

6 SIMULATION RESULTS

In this section, we evaluate the proposed *band selection* approach against homogeneous band access approaches, for steady DSA overlay topology in terms of the following performance metrics: (i) *Energy Efficiency* - the average amount of energy consumed to transfer a generated message from a sensor block to the intended data center, (ii) *Message Delivery Ratio (MDR)* - the fraction of total messages delivered to the data center within the TTL deadline, to the total generated messages at all sensor blocks, and (iii) *Network Latency* - the average delay incurred (i.e., total transmission delay, propagation delay and queuing delay at each intermediate node) in delivering all messages, each from its block to the data center.

Each of the above performance metrics is evaluated against the following parameters: (a) varying message size, (b) varying TTL deadline, and (c) varying source-destination pair distance. The first two parameters represent the heterogeneity in various messages, while the third one represents the heterogeneity in geographical distance between the sensor blocks and data centers.

Simulation Settings: We develop a Java simulator to simulate a SCC scenario with 5 data centers, 15 CPEs, 30 sensor blocks, each with 50-100 sensing agents. On average, each CPE periodically visits 2 CPEs with a round trip time of 1 hour. The steady DSA overlay topology consists of 200 DSA nodes (e.g., public buses, RSUs etc.). Now 50% of overlay nodes (imitating RSUs) are randomly placed and are static whereas other overlay nodes (imitating public buses) move over a fixed trajectory. We consider that each DSA enabled node has the knowledge of location and spectrum availability at every other node in the network. Unless otherwise stated, the message size, TTL deadline and farthest distance between sensor blocks and data centers are taken as 250 MB, 6 hours, and 45 Km for the experiments, respectively.

Each band has a FCC mandated maximum allowable transmit power which can not be exceeded by any node operating on a DSA basis. Hence, we consider a transmit power (1 W (30 dBm)) which is allowable on a secondary basis, in all ISM, TV, LTE and CBRS bands. The values of other controlling parameters are as follows: path loss factor $\alpha = 3.5$ (sub-urban area), *SINR* = -75 dBm (3.16×10^{-8} mW), and received power threshold (τ) = -20 dBm (0.01 mW).

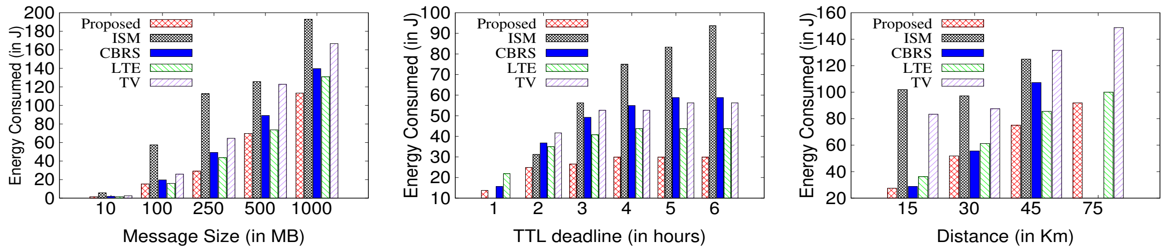
6.1 Energy Efficiency

Figs. 4(a), 4(b), and 4(c) clearly show that the energy consumed by our proposed approach is significantly lower than all homogeneous band approaches across various message sizes, TTL deadlines and source-destination distances. The average amount of energy saved by our approach is 36.2%, 47%, and 42.2% against all other approaches combined (whereas 15%, 20% and 13% against the best one), for various message sizes, TTL deadlines and distances, respectively. This is because our approach selects a suitable band at each intermediate node for enhancing energy efficiency unlike scenarios where the node is restricted to access only one predetermined band.

Note that in Fig. 4(c), the energy consumed is 0 J for distance 75Km for ISM and CBRS bands. This is because there existed no intermediate nodes in the communication range, that could forward the message from the sensor block towards the data center. Hence, no energy was consumed at any node in the DSA overlay network. However, the message delivery ratio is negligible ($\approx$ 0%) (Fig. 5(c)), hence defeating the purpose of SCC. The proposed approach achieves the highest energy efficiency, yet satisfying QoS.

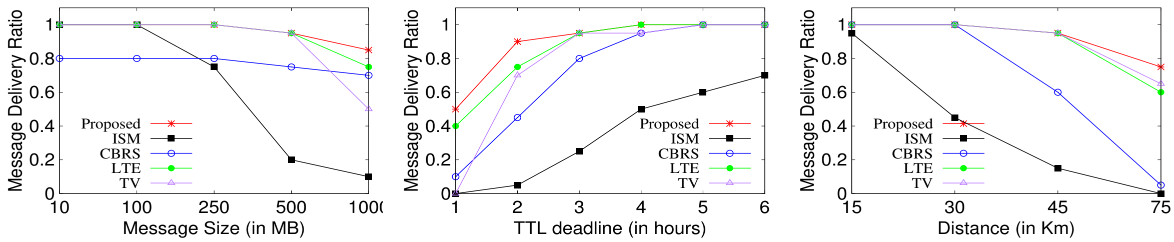
6.2 Message Delivery Ratio

As illustrated in Figs. 5(a), 5(b), and 5(c), our approach yields either comparable or better message delivery ratio (MDR) compared to that of homogeneous band approaches, irrespective of varying message sizes, TTL deadlines and distances between the sensor block and data center, respectively. The improvement in MDR for our approach is almost 15% for message size (> 500Mb), 17% for TTL



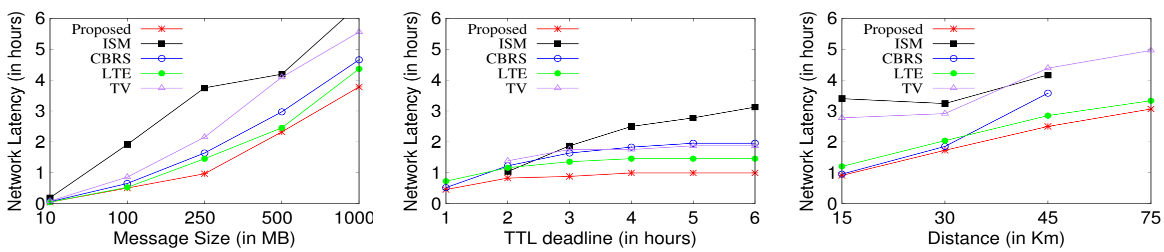
(a) (b) (c)

Figure 4: Energy Efficiency: (a) Message Size, (b) TTL, and (c) Distance between sensor block and data center



(a) (b) (c)

Figure 5: Message Delivery Ratio: (a) Message Size, (b) TTL, and (c) Distance between sensor block and data center



(a) (b) (c)

Figure 6: Network Latency: (a) Message Size, (b) TTL, and (c) Distance between sensor block and data center

deadline (< 3 hours) and 10% for distance (> 50 Km), compared to the best of homogeneous bands, i.e., LTE Band for first two cases and TV Band for the third one. This is because our proposed TcE algorithm simultaneously accounts for TTL besides enhancing the energy savings. Hence, the proposed approach always guarantees the highest MDR for any message with varying heterogeneity demand. However, the homogeneous band approach do not have the flexibility of choosing any other band than the pre-specified one, thereby incurring poor MDR.

6.3 Network Latency

Figs. 6(a), 6(b), and 6(c) show that the proposed approach achieves better network latency compared to other approaches, irrespective of message and geographical heterogeneity. This is because our approach attempts to choose the path with least message transmission time while determining the TcE path (from Eq. 2). Specifically, our approach improves the network latency by almost 16%, 23% and 14% compared to the best of homogeneous band approaches (i.e., LTE), for varying message sizes, TTL deadlines and geographical distances, respectively.

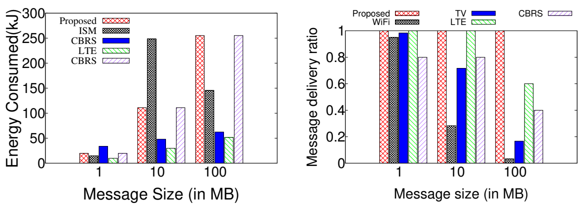
Again note that the network latency for ISM and CBRS bands are not shown for distance = 75 Km (see Fig. 6(c)). This is because their network latency is equivalent to infinity as no messages were successfully delivered to their intended data centers, within their TTL deadlines (see Fig. 5(c)).

7 VARIABLE DSA TOPOLOGY

To realize the true power of ubiquitous connectivity, we believe the private smart vehicles of the future could also be harnessed as members of the DSA overlay network. However, since mobility in such cases is not controlled due to variables routes, constructing a global knowledge might be impossible. We investigate certain challenges and a road map for energy efficient band selection under such topologies. Due to the lack of global knowledge, we investigate a simple greedy approach that attempts to choose the locally optimized energy-efficient band at any given node for any message $m < u, v, L, T >$, hopefully leading to the end-to-end energy efficiency while meeting the TTL deadline.

The greedy algorithm selects the band $s \in S$ at any given node u for any message m only if the following conditions are met: (i) if the next hop is the destination node, or (ii) the energy consumed over selected band s is the least, the latency cost is less than the TTL and there exists at least two nodes in the communication range over the selected band s. These conditions are important to improve the chances of successful data delivery to the destination node. Once the suitable energy-efficient band s is selected at the current node

u, it floods the messages over the selected band s to all neighboring nodes that lie in the communication range. The time complexity of the algorithm is $O(|V| \times |S|)$ where $|V|$ and $|S|$ are the total number of nodes and band types, respectively.



(a) (b)

Figure 7: Variable DSA Overlay Network: (a) Energy Efficiency, and (b) Message Delivery Ratio

Challenges and Future Roadmap: Let us investigate the performance of the greedy local optimization in variable DSA topology, and draw key challenges and a future roadmap for further research. From Fig. 7(b), it is evident that the proposed greedy approach outperforms others in terms of MDR, however, it suffers in terms of energy efficiency compared to that of other homogeneous band access approaches (see Fig. 7(a)). This is mainly due to various contextual factors, such as unpredictable node mobility patterns, node contact behaviors, etc. The results are similar for other two parameters (plots not shown here for lack of space).

We conclude that a locally optimized greedy solution alone is not an apt solution to improve the end-to-end energy efficiency via dynamic band selection. In fact, the optimization under that case should be complemented by an efficient delay tolerant routing protocol that reduces the unpredictability of determining the best set of intermediate nodes by learning geographical contextual factors and contact mobility patterns. Therefore, we plan to investigate the contextual factors and come up with a spectrum and mobility aware approach that improves the end-to-end energy efficiency for any given message that also meets the TTL deadline in such a challenging variable DSA topology scenario.

8 CONCLUSION

In this paper, we proposed a novel architecture that uses a small number of DSA enabled devices for forming a DSA overlay network on top of the legacy infrastructure. The goal is to enhance end-to-end energy efficiency while guaranteeing QoS. We discussed how EM characteristics can be exploited for intelligent matching of any message requirement to a suitable band. We also formulated a constrained optimization problem and proposed a dynamic programming approach for determining TTL constrained energy-efficient path for any given message with heterogeneous requirement. Compared to the homogeneous band access approaches, the proposed approach excels in terms of energy efficiency while satisfying QoS, irrespective of message and geographical heterogeneity, and thus bypassing under- and over-provisioning issues.

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