A Broadcasting Scheme for Infrastructure to Vehicle Communications

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***Abstract*— A large set of potential applications being designed for Intelligent Transportation Systems (ITS) depend on the broadcasting of information and control packets by roadside infrastructure points to vehicles in their vicinity. This paper considers the transport capacity of broadcast schemes and evaluates and compares the transport capacity of strategies based on time-splitting, frequency-splitting and superposition coding. A proportionally fair broadcast scheduling algorithm is then proposed and its performance compared against other schedulers.**

I. Introduction

In a typical ITS system application such as traffic advisories, road condition information, local maps and restaurants, etc. a roadside infrastructure point may want to deliver different information to vehicles in different geographical locations. There is an inherent tradeoff between the rate of transmissions and the distance till which they may be correctly decoded, as characterized by the well known Shannon's channel coding theorem [11]. Thus a key decision that the scheduler associated with a broadcasting station has to make is: *which region to broadcast to and at what rate, in order to maximize the throughput while maintaining fairness?* This is the problem addressed in this paper.

To address this problem, this paper uses the notion of transport capacity developed in [5] to determine the utility associated with a broadcast packet. Gupta and Kumar define the transport capacity of a transmission as the product of the rate and the distance it traverses with multiple credit being given for broadcast and multicast packets [5]. This paper compares the transport capacity of broadcast schemes based on various transmission strategies. Finally, a proportionally fair scheduling policy is proposed that strives to maximize the transport capacity while maintaining fairness.

For a given bandwidth and transmission power, a typical broadcast strategy would be to either use the entire available bandwidth to transmit to different regions over different periods of time (time-splitting) or to split the available bandwidth into non-overlapping bands and transmit to different regions simultaneously over different bands (frequency-splitting). In [7] the author proposes variations of centralized and decentralized time-splitting mechanisms. Technologies based on both time and frequency-splitting for infrastructure to vehicular communications are considered in [8], [9]. Much of the existing literature on broadcast protocols for vehicular networks are for the multi-hop case with the focus on reducing the number of re-broadcasts and are aimed primarily at ad hoc networks and vehicle-vehicle communications [1]. These papers do not address the problem considered in this paper. Finally, while code division multiplexing may also be used for vehicular communications [3], [10], the dynamic reallocation of codes as vehicles move to different parts of the network introduces additional overhead and is thus not considered in this paper.

The rest of the paper is organized as follows. Section II compares the transport capacities of different transmission strategies. Section III presents the proportionally fair scheduling algorithm. Finally, Section IV presents the simulation results while Section V presents the concluding remarks.

II. Communication Strategies

This section considers three communication strategies and evaluates them in terms of their transport capacity: time-splitting, frequency-splitting and superposition coding. While the Shannon capacity of these schemes is well known [2], this paper considers the notion of transport capacity.

A. Transport Capacity

This section formally defines the notion of the transport capacity of a broadcast packet based on [5]. Consider a communication system with a transmission power of P watts where the transmitter and receiver are separated by a distance of d meters. The channel bandwidth is assumed to be W Hz and the communication channel is subject to additive white Gaussian noise with power spectral density of N_o watts/Hz. A transmitted signal is assumed to decay according to $d^{-\alpha}$ with distance, where α is the channel attenuation constant and assumed to be $\alpha > 2$. All antenna and system parameters are assumed to be 1. Shannon's theorem on channel capacity then states that considering all coding schemes, the largest rate C at which the transmitter may send messages with arbitrarily low bit error rates to the receiver is given by [11]

$$C = W \log_2 \left(1 + \frac{Pd^{-\alpha}}{WN_o}\right) \tag{1}$$

Since a broadcast packet conveys information targeted to all nodes that receive it, the transport capacity associated with the transmission is a function of the transmission rate, the distance it traverses, as well as the number of nodes that receive the packet. If the region around the transmitter where vehicles may successfully receive the broadcast packet can be described by a circular region with radius d_{max}, the transport capacity of the transmission is defined as

$$U = C(d_{max})^{\gamma} \tag{2}$$

where γ is a parameter that can be selected to represent the relationship between the transmission range and the number of vehicles. The parameter is bounded by $1 \leq \gamma < 2$ since the road lengths and parking areas grow at least linearly with the radius but not faster than $(d_{max})^2$.

Commercial wireless communication systems are built to transmit at one or more predefined rates. For example, devices complying to the IEEE 802.11a standards may transmit at 6, 9, 12, 18, 24, 36, 48 and 54 Mbps and employ different modulation and coding schemes for different rates. Given that a transmitter needs to convey information to receivers at geographically diverse locations, different modulation and coding schemes may be used to select the rate and split the available power and bandwidth. To keep the discussion simple, this section assumes that two modulation and coding schemes are available to the infrastructure point transmitter corresponding to rates of $C1$ and $C2$. Without loss of generality, we assume that $C1 < C2$. The transport capacity of the three communication strategies are evaluated next.

B. Time Splitting

In the time-splitting strategy, the transmitter alternates between transmitting at rates of $C1$ and $C2$ and uses the entire spectrum and power for each rate. We denote by τ the fraction of time that the transmitter devotes to rate $C1$ while the remaining $1-\tau$ is spent transmitting at rate $C2$. Let d_1 and d_2 denote the maximum distance till which error free transmissions may be received at rates of $C1$ and $C2$, respectively. From Eqn. (1) we then have

$$d_i = \left[\frac{P}{WN_o(2^{Ci/W}-1)}\right]^{\frac{1}{\alpha}} \tag{3}$$

where d_i and Ci, $i = 1, 2$ correspond to the two modulation and coding schemes. Since a rate of $C1$ is achieved for a fraction τ of the time while $C2$ is achieved for $1-\tau$, the transport capacities that can be achieved by time-splitting is

$$U_i^{TS} = \tau C1 \left[\frac{P}{WN_o(2^{C1/W}-1)}\right]^{\frac{\gamma}{\alpha}} \tag{4}$$

$$U_i^{TS} = (1-\tau) C2 \left[\frac{P}{WN_o(2^{C2/W}-1)}\right]^{\frac{\gamma}{\alpha}} \tag{5}$$

and τ may be varied in the interval $[0, 1]$.

C. Frequency Splitting

With frequency-splitting, transmissions at both rates may be carried out simultaneously by splitting the available bandwidth into two non-overlapping bands. Additionally, the available power may also be split between the two transmissions to control the distance till which error free communications may be made at either rate. Denote by δ and $1-\delta$, $0 \leq \delta \leq 1$, the fraction of the bandwidth allocated to transmissions at rate $C1$ and $C2$, respectively. Also, let ϵ and $1-\epsilon$ denote the fraction of available power devoted to transmissions at rate $C1$ and $C2$, respectively. For a receiver at a distance d from the sender transmitting with power ϵP and bandwidth δW, the maximum achievable error free communication rate is

$$C = \delta W \log_2\left(1 + \frac{\epsilon P d^{-\alpha}}{\delta W N_o}\right) \tag{6}$$

The maximum distances till which transmissions at arbitrarily low error rates can then be received for the two modulation and coding schemes is then given by

$$d_i = \left[\frac{\epsilon_i P}{\delta_i W N_o(2^{Ci/\delta_i W}-1)}\right]^{\frac{1}{\alpha}} \tag{7}$$

where $i \in \{1, 2\}$ corresponding to transmissions at rate $C1$ and $C2$ respectively and $\epsilon_1 = \epsilon$, $\epsilon_2 = 1-\epsilon$, $\delta_1 = \delta$ and $\delta_2 = 1-\delta$. The corresponding transport capacities are then

$$U_1^{FS} = C1 \left[\frac{\epsilon P}{\delta W N_o(2^{C1/\delta W}-1)}\right]^{\frac{\gamma}{\alpha}} \tag{8}$$

$$U_2^{FS} = C2 \left[\frac{(1-\epsilon) P}{(1-\delta) W N_o(2^{C2/(1-\delta) W}-1)}\right]^{\frac{\gamma}{\alpha}} \tag{9}$$

The parameters δ and ϵ can be varied independently in the range $[0, 1]$ to obtain the entire range of achievable transport capacity points.

D. Superposition Coding

With superposition coding, in addition to sending a message to a primary receiver, the transmitter superimposes an additional message destined to a secondary receiver on top of the message destined for the primary receiver [4]. The available transmission power is split between these two transmissions. The primary receiver decodes its packet while treating the superimposed signal as interference. The secondary receiver decodes its packet using successive interference cancellation. If the distances from the transmitter to the primary and secondary receivers are d_1 and d_2 respectively and a fraction β of the power is spent on the primary transmission, the achievable rates to the two receivers is given by

$$C_1 = W \log_2\left(1 + \frac{\beta P d_1^{-\alpha}}{(1-\beta) P d_1^{-\alpha} + W N_o}\right) \tag{10}$$

$$C_2 = W \log_2\left(1 + \frac{(1-\beta) P d_2^{-\alpha}}{W N_o}\right) \tag{11}$$

To ensure that the secondary receiver is able to decode the primary transmission whenever the primary receiver is able to, and also to ensure that the remaining signal after the subtraction has a sufficiently high signal to noise ratio, the channel quality to the secondary receiver should be better than that of the primary receiver. Thus vehicles in a nearer region can operate as the secondary receivers while those in a region further away may serve as primary receivers. Given that the infrastructure point can only transmit at rates $C1$ and $C2$, substituting $C_1 = C1$ and $C_2 = C2$ in Eqns. (10) and (11) and solving for d_1 and d_2, the maximum distances till which superposition coding may be successfully employed are

$$d_1 = \left[\frac{P-(1-\beta)P2^{C1/W}}{WN_o(2^{C1/W}-1)}\right]^{\frac{1}{\alpha}} \quad (12)$$

$$d_2 = \left[\frac{(1-\beta)P}{WN_o(2^{C2/W}-1)}\right]^{\frac{1}{\alpha}} \quad (13)$$

Note that Eqn. (12) implies that the power allocated to the secondary transmissions must be kept sufficiently small in order to make superposition coding feasible. Specifically, the fraction of power allocated to secondary transmissions should satisfy $(1-\beta) < \frac{1}{2^{C1/W}}$ to ensure $d_1 > 0$. When this condition is satisfied, the transport capacities associated with the superposition coding based broadcast are then given by

$$U_1^{SC} = C1\left[\frac{P-(1-\beta)P2^{C1/W}}{WN_o(2^{C1/W}-1)}\right]^{\frac{\gamma}{\alpha}} \quad (14)$$

$$U_2^{SC} = C2\left[\frac{(1-\beta)P}{WN_o(2^{C2/W}-1)}\right]^{\frac{\gamma}{\alpha}} \quad (15)$$

When $(1-\beta) \geq \frac{1}{2^{C1/W}}$, only one set of transmissions is feasible and the achievable transport capacity points (U_1^{SC}, U_2^{SC}) belong to the set $(0, U_2^{SC})$. The parameter β can be varied over the range $[0,1]$ to obtain the entire range of achievable transport capacity points.

E. Dominance Results for Superposition Coding

This section shows that unlike Shannon capacity where superposition coding always dominates, when the transport capacity is considered, frequency-splitting may dominate superposition coding under certain scenarios. Conditions determining these scenarios are also derived. We first start with scenarios where superposition coding dominates.

Claim 1: If the fraction of bandwidth δ allocated to transmissions at rate $C1$ under frequency-splitting satisfies $(1-\delta)(2^{C2/(1-\delta)W}-1) \geq 2^{C1/W}(2^{C2/W}-1)$, for any transport capacity point (U_1^{FS}, U_2^{FS}) achievable using frequency-splitting, there exists a transport capacity point (U_1^{SC}, U_2^{SC}) achievable using superposition coding that dominates it in the sense

$$U_1^{SC} \geq U_1^{FS} \quad (16)$$

$$U_2^{SC} \geq U_2^{FS} \quad (17)$$

where $U_1^{FS}, U_2^{FS}, U_1^{SC}$ and U_2^{SC} are given by Eqns. (8), (9), (14) and (15) respectively. The inequalities are strictly satisfied in all cases except when $\epsilon = 0$ and $(1-\delta)(2^{C2/(1-\delta)W}-1) = 2^{C1/W}(2^{C2/W}-1)$ or $\delta = 1$ and $\epsilon = 1$ when the expressions hold with an equality.

Proof: Pick any transport capacity point achievable by frequency-splitting as specified by a choice of δ and ϵ with $(1-\delta)(2^{C2/(1-\delta)W}-1) > 2^{C1/W}(2^{C2/W}-1)$. Now,

$$\begin{aligned}\frac{(1-\epsilon)(2^{C2/W}-1)}{(1-\delta)(2^{C2/(1-\delta)W}-1)} &< \frac{(1-\epsilon)(2^{C2/W}-1)}{2^{C1/W}(2^{C2/W}-1)} = \frac{1-\epsilon}{2^{C1/W}} \\ &\leq \frac{1}{2^{C1/W}} \end{aligned} \quad (18)$$

Using the result above to ensure its feasibility, select $1-\beta$ such that

$$\frac{(1-\epsilon)(2^{C2/W}-1)}{(1-\delta)(2^{C2/(1-\delta)W}-1)} < 1-\beta \leq \frac{1}{2^{C1/W}} \quad (19)$$

The transport capacity associated with the transmissions at rate $C1$ then satisfies

$$\begin{aligned} U_1^{SC} &= C1\left[\frac{P-(1-\beta)P2^{C1/W}}{WN_o(2^{C1/W}-1)}\right]^{\frac{\gamma}{\alpha}} \\ &> C1\left[\frac{P-\frac{1}{2^{C1/W}}\left(1-\frac{\epsilon(2^{C1/W}-1)}{\delta(2^{C1/\delta W}-1)}\right)P2^{C1/W}}{WN_o(2^{C1/W}-1)}\right]^{\frac{\gamma}{\alpha}} \\ &= C1\left[\frac{\epsilon P}{\delta WN_o(2^{C1/\delta W}-1)}\right]^{\frac{\gamma}{\alpha}} = U_1^{FS} \end{aligned} \quad (20)$$

The transport capacity associated with the transmissions at rate $C2$ satisfies

$$\begin{aligned} U_2^{SC} &= C2\left[\frac{(1-\beta)P}{WN_o(2^{C2/W}-1)}\right]^{\frac{\gamma}{\alpha}} \\ &> C2\left[\frac{\frac{(1-\epsilon)(2^{C2/W}-1)}{(1-\delta)(2^{C2/(1-\delta)W}-1)}P}{WN_o(2^{C2/W}-1)}\right]^{\frac{\gamma}{\alpha}} \\ &= C2\left[\frac{(1-\epsilon)P}{(1-\delta)WN_o(2^{C2/(1-\delta)W}-1)}\right]^{\frac{\gamma}{\alpha}} = U_2^{FS} \end{aligned}$$

Next, consider the special case where $\epsilon = 0$ and $(1-\delta)(2^{C2/(1-\delta)W}-1) = 2^{C1/W}(2^{C2/W}-1)$. The transport capacities associated with frequency-splitting in this case can be compared with the special case of superposition coding when $1-\beta = \frac{1}{2^{C1/W}}$.

$$U_1^{FS} = 0 = U_1^{SC} \quad (21)$$

$$\begin{aligned} U_2^{FS} &= C2\left[\frac{P}{(1-\delta)WN_o(2^{C2/(1-\delta)W}-1)}\right]^{\frac{\gamma}{\alpha}} \\ &= C2\left[\frac{(1-\beta)P}{WN_o(2^{C2/W}-1)}\right]^{\frac{\gamma}{\alpha}} = U_2^{SC} \end{aligned} \quad (22)$$

Finally, when $\delta = 1$ and $\epsilon = 1$, compare the associated frequency-splitting transport capacities with the special case of superposition coding when $\beta = 1$. This gives,

$$U_1^{FS} = C1\left[\frac{P}{WN_o(2^{C1/W}-1)}\right]^{\frac{\gamma}{\alpha}} = U_1^{SC} \quad (23)$$

$$U_2^{FS} = 0 = U_2^{SC} \quad (24)$$

which completes the proof. ■

The condition $(1-\delta)(2^{C2/(1-\delta)W}-1) \geq 2^{C1/W}(2^{C2/W}-1)$ which ensures the dominance of superposition coding transport capacities is related to the fraction of the bandwidth δ that is allocated to transmissions at rate $C1$ by the frequency-splitting scheme. Consider the transport capacity associated with the superposition coding scenario where $1-\beta = \frac{1}{2^{C1/W}}$ as given in Eqns. (21) and (22). Simultaneous transmissions at both rates are possible as β is increased beyond this point.

The condition $(1-\delta)(2^{C2/(1-\delta)W}-1) \geq 2^{C1/W}(2^{C2/W}-1)$ ensures that even if all the available power is allocated to transmissions at rate $C2$, the available bandwidth $(1-\delta)W$ is not sufficient for the frequency-splitting transport capacities to dominate those of superposition coding. The following result shows the conditions under which frequency-splitting dominates superposition coding.

Claim 2: If the fraction of bandwidth δ allocated to transmissions at rate $C1$ under frequency-splitting satisfies $(1-\delta)(2^{C2/(1-\delta)W}-1) < 2^{C1/W}(2^{C2/W}-1)$ and $1-\beta > \frac{1}{2^{C1/W}}$, for any transport capacity point (U_1^{SC}, U_2^{SC}) achievable using superposition coding, there exists a transport capacity point (U_1^{FS}, U_2^{FS}) that dominates it in the sense

$$U_1^{FS} \geq U_1^{SC} \tag{25}$$

$$U_2^{FS} \geq U_2^{SC} \tag{26}$$

where $U_1^{FS}, U_2^{FS}, U_1^{SC}$ and U_2^{SC} are given by Eqns. (8), (9), (14) and (15) respectively. The inequalities are strictly satisfied in all cases except when $\epsilon = 0$ and $\delta = 0$ when the expressions hold with an equality.

Proof: The proof is similar to that for Claim 1. ■

III. Broadcast Scheduling Algorithm

This section presents a proportionally fair algorithm for scheduling broadcast packets. We consider a static infrastructure point that needs to broadcast packets generated by the ITS to vehicles in its vicinity. In addition to maximizing the throughput, we also aim to maintain fairness between the vehicles in different regions with respect to their throughput.

The region around an infrastructure point is divided into k circular regions. The radius of the i-th region is denoted by r_i with $r_1 < r_2 < \cdots < r_k$. Broadcast packets arrive for region i at rate a_i. We assume that the transmitter at the roadside infrastructure point can transmit at two possible modulation and coding schemes corresponding to bit rates of $C1$ and $C2$ with $C1 < C2$. Given a maximum transmission power P, we denote by d_1^{max} and d_2^{max} the maximum distance till which transmissions at rate $C1$ and $C2$, respectively, can be received with arbitrarily low error rates. We assume that $r_k \leq d_1^{max}$ to keep the problem practical and concern ourselves only with scenarios where the entire region of interest is covered by the transmissions. We denote by R_i, $R_i \in \{C1, C2\}$ the highest error free transmission rate that can be sustained in the whole of region i by the infrastructure point.

The scheduler needs to decide which region to transmit the next broadcast packet to and what rate to use. Let a broadcast packet be transmitted to region i at rate $C1$. The minimum fraction β of the available power P that needs to be spent can be obtained by substituting r_i for d in Eqn. (10) and solving for β. We then have

$$\beta = \frac{(WN_o + Pr_i^{-\alpha})(2^{C1/W}-1)}{Pr_i^{-\alpha}2^{C1/W}} \tag{27}$$

Substituting this value of β in Eqn. (13), we obtain the distance till which error free transmissions at rate $C2$ can be made given that region i can receive transmissions at rate $C1$. We denote by D_i^2 the farthest region, the whole of which can receive error free transmissions at rate $C2$ given that region i can receive transmissions at rate $C1$. Similarly, the minimum fraction $1-\beta$ of the available power that needs to be spent to ensure error free communications to region i, $r_i \leq d_2^{max}$, can be obtained from Eqn. (11) and is given by

$$1-\beta = \frac{WN_o r_i^{-\alpha}(2^{C2/W}-1)}{P} \tag{28}$$

If $1-\beta < \frac{1}{2^{C1/W}}$, simultaneous transmission at rate $C1$ using superposition coding is possible. We denote the farthest region, the whole of which can receive error free transmissions at rate $C1$, given that region i is receiving transmissions at rate $C2$, by D_i^1. D_i^1 can be obtained by substituting β from the equation above in Eqn. (12) and solving for d. We use $D_i^1 = 0$ and $D_i^2 = 0$ if no superposition coding is possible.

The pseudo-code for the algorithm is shown in Algorithm 1. Depending on the primary region $i^*(n)$ selected by the scheduler, it may not always be feasible to use superposition coding to simultaneously broadcast packets to another region. Such a situation arises when the power required to transmit at rate $C2$ is high enough to cause significant interference to the transmissions at rate $C1$. As shown in Section II-D, this occurs when $(1-\beta) \geq \frac{1}{2^{C1/W}}$. In these situations it was shown that frequency multiplexing can lead to higher transport capacities. The scheduling algorithm developed in this section resorts to a special case of frequency multiplexing when superposition coding is not feasible.

IV. Simulation Results

This section presents simulation results to compare the performance of the proposed scheduler with some other possibilities. The simulations were done with a custom built simulator written in C. To keep the results general, normalized values were used for most parameters. The parameter values used were: $W = 1$, $N_o = 1$ and $P = 1$. Results are reported for two sets for transmissions rates: $C1 = 0.1$, $C2 = 0.5$ and $C1 = 0.2$, $C2 = 0.5$. The entire network is divided into ten circular regions centered at the infrastructure point. The radius r_i of region i satisfies $r_i = ir_1$. The radius of the farthest region equals the maximum distance till which transmissions at rate $C1$ may be made with arbitrarily low error rates.

For evaluating the throughput, the transmission time for a broadcast packet at rate $C1 = 0.1$ is assumed to be equal to one time unit. The packet transmission times at other rates are scaled with respect to this unit of time. For evaluating the fairness, Jain's fairness index is used [6]. If the throughput of region i at time t is denoted by $x_i(t)$, Jain's fairness index $F(t)$ at time t is then given by $F(t) = \frac{\left(\sum_{i=1}^{n} x_i(t)\right)^2}{n\sum_{i=1}^{n} x_i(t)^2}$ which attains the value of 1 only when the allocation is totally fair $(x_1(t) = x_2(t) = \cdots = x_n(t))$.

Table I compares the performance of the proposed scheduler with two others: (1) a scheduler that broadcasts messages to different regions following a round robin policy and (2) a scheduler that always selects the region which supports the

Algorithm 1 Proportionally fair scheduling algorithm.

Initialize $T_i(0)$ to a constant value for all i, $n = 0$ and evaluate R_i^1 and R_i^2 for all i
while (1) **do**
  pick the next region $i^*(n)$ to transmit: $i^*(n) = \arg\max_{i=1,\cdots,k} \frac{R_i}{T_i(n)}$
  if $R_{i^*(n)} = C1$ **then**
    if $D^2_{i^*(n)} > 0$ **then**
      pick the additional region $j^*(n)$ to transmit to: $j^*(n) = \arg\max_{j=1,\cdots,D^2_{i^*(n)}} \frac{C2}{T_i(n)}$
      transmit one packet at rate $C1$ to region $i^*(n)$ and $\lfloor \frac{C2}{C1} \rfloor$ packets to region $j^*(n)$ at rate $C2$
      update $T_i(n+1)$: $T_i(n+1) = \begin{cases} \left(1-\frac{1}{t_c}\right)T_i(n) + \frac{1}{t_c} & i = i^*(n) \\ \left(1-\frac{1}{t_c}\right)T_i(n) + \frac{1}{t_c}\lfloor\frac{C2}{C1}\rfloor & i = j^*(n) \\ \left(1-\frac{1}{t_c}\right)T_i(n) & \text{otherwise} \end{cases}$
    else
      transmit one packet at rate $C1$ to region $i^*(n)$
      update $T_i(n+1)$: $T_i(n+1) = \begin{cases} \left(1-\frac{1}{t_c}\right)T_i(n) + \frac{1}{t_c} & i = i^*(n) \\ \left(1-\frac{1}{t_c}\right)T_i(n) & \text{otherwise} \end{cases}$
    end if
  else
    if $D^1_{i^*(n)} > 0$ **then**
      pick the additional region $j^*(n)$ to transmit to: $j^*(n) = \arg\max_{j=1,\cdots,D^1_{i^*(n)}} \frac{C1}{T_i(n)}$
      transmit $\lfloor \frac{C2}{C1} \rfloor$ packets at rate $C2$ to region $i^*(n)$ and one packet to region $j^*(n)$ at rate $C1$
      update $T_i(n+1)$: $T_i(n+1) = \begin{cases} \left(1-\frac{1}{t_c}\right)T_i(n) + \frac{1}{t_c}\lfloor\frac{C2}{C1}\rfloor & i = i^*(n) \\ \left(1-\frac{1}{t_c}\right)T_i(n) + \frac{1}{t_c} & i = j^*(n) \\ \left(1-\frac{1}{t_c}\right)T_i(n) & \text{otherwise} \end{cases}$
    else
      transmit one packet at rate $C2$ to region $i^*(n)$
      update $T_i(n+1)$: $T_i(n+1) = \begin{cases} \left(1-\frac{1}{t_c}\right)T_i(n) + \frac{1}{t_c} & i = i^*(n) \\ \left(1-\frac{1}{t_c}\right)T_i(n) & \text{otherwise} \end{cases}$
    end if
  end if
  $n = n + 1$
end while

highest data rate (ties are broken randomly). The round robin scheduler is chosen because of its fairness properties while the other one is chosen because of its throughput performance. The results in Table I are for 1000 iterations of the scheduler's operation. The results show that the proposed scheduler is a good compromise between throughput and fairness.

Scheme	$C1 = 0.1$, $C2 = 0.5$	
	Throughput	Fairness
Maximum Throughput	5.00	0.59
Round Robin	1.92	0.99
Proportionally Fair	1.96	0.86

TABLE I
COMPARISON OF VARIOUS SCHEDULING POLICIES

t_c	$C1 = 0.1$, $C2 = 0.5$		$C1 = 0.2$, $C2 = 0.5$	
	Throughput	Fairness	Throughput	Fairness
10	5.30	0.80	5.50	0.92
100	5.40	0.79	5.58	0.91
500	5.90	0.76	5.90	0.83

TABLE II
EFFECT OF PARAMETERS OF PROPORTIONALLY FAIR SCHEDULING

Table II evaluates the impact of t_c on the scheduler's performance. This parameter controls the time horizon over which the scheduler maintains fairness. It can be observed that as t_c increases, the scheduler achieves lower fairness but higher throughput. The results reported here are again after 1000 rounds of the scheduler's operation. The difference in the performance in terms of both throughput and fairness, however, reduces as the scheduler runs for longer periods.

V. CONCLUSIONS

This paper considers the problem of transmission of broadcast packets by roadside infrastructure points. The transport capacity of a broadcast packet is analyzed and compared for three transmission strategies. It is shown that frequency-splitting may dominate superposition coding in certain scenarios. Finally, a proportionally fair scheduler for transmitting broadcast packets is proposed.

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