WiFiRe: Rural Area Broadband Access using the WiFi PHY and a Multisector TDD MAC[†]

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Abstract— **The needs of Indian rural telecom, and the economics of currently available broadband access technologies, motivate a new system for rural broadband access, which we call WiFiRe (WiFi Rural Extension). The system leverages the widely available, and highly cost-reduced, WiFi chipsets. We, however, retain only the PHY from these chipsets and propose a single-channel, multisector, TDD MAC using directional antennas. The proposed WiFiRe MAC is similar to the WiMAX MAC in several respects. In this paper, we motivate our approach, describe the system architecture and the MAC, analyse the spatial reuse, and then, using a simple scheduler, provide an assessment of the voice and data capacity of a WiFiRe system.**

I. THE INDIAN RURAL SCENARIO

About 70% of India's population, or 750 million, live in its 600,000 villages. More than 85% of these villages are on a flat terrain. On an average, a village has 250 households (situated in a cluster), and its size, including farmland, is 5 sq. km. Villages are spaced 2 km to 3km apart and are spread out in all directions from the market towns, which are spaced 30-40 km apart. Each such town serves a catchment of around 250-300 villages.

The optical telecom backbone networks of multiple service providers pass through these towns. India's mobile revolution [1] has fueled this growth, and a lot of dark fiber is available. However, the telecom backbone ends abruptly at the towns and the larger villages. Beyond that, cellular coverage from the base stations in these towns extends mobile telephony up to a radius of 5 km, and then telecommunications simply peters out. As cellular telephony is highly sought after, the networks will expand rapidly, making it more affordable to the rural populace [1]. Also, fixed wireless telephones that support Internet access at dial-up speeds have been provided in tens of thousands of villages as a service obligation.

The rural per capita income is distinctly lower than the national average. Only 2.5% of households earn in excess of US$ 500 per month [1], and can even aspire to have a personal computer and an Internet connection. For the majority, however, with an average monthly household income of US$ 60, a public kiosk (that has a basket of services) can serve the need for Internet access, or even telephony, both of which are enablers for wealth creation [2].

When considering a technology for rural India, affordability determines its economic sustainability. Assuming an average spend of US$ 1 per month (2% of income) per household on kiosk services, the revenue of a public kiosk can only be of the order of US$ 125 month (assuming two kiosks per village). Not more than US$ 25 from this revenue can go to the connectivity provider if the kiosk is to be a sustainable business. In mobile telephony, the ratio of capital expenditure (capex) on the access network to sustainable monthly revenue per user in India is currently less than 12. If we use the same factor, the capex per kiosk can be at most US$ 300, and this would include the subscriber-side wireless equipment as well.

It is clear that the "last mile" from town to village has to be wireless. A star topology with a BS at the town serving the surrounding villages is a proven model. Mesh topologies are being studied as an alternative [3]. A BS can be expected to serve about 250-300 connections initially, going up to a 1000 connections in a few years. Given the cost target, only a wireless technology that leverages mass-market components, such as DECT or WiFi [2], is viable. Custom-built technologies, or emerging technologies at the early induction stage such as WiMAX, are too costly [2].

II. A BROADBAND WIRELESS TECHNOLOGY FOR RURAL INDIA: REQUIREMENTS

Even with a modest, average bit-rate of 64 kbps per kiosk during busy hours, 500 kiosks will generate traffic

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of the order of 30 Mbps to evacuate over the air per Base Station site. This is non-trivial today, even with a spectrum allocation of 10-15 MHz, unless sectorized deployment with spectrum reuse is employed. The broadband wireless access system employed to provide Internet service to kiosks must also provide public telephony using VoIP technology, as telephony earns far higher revenue per bit than any other service. It is interesting to note that though the volume of teletraffic is limited, by the village income level[1], to less than 1 Erlang per kiosk during the busy hours, it is not an insignificant load on the system. An efficient VoIP capability with guaranteed QoS must thus be *built into the system by design*.

III. MOTIVATION FOR WIFIRE

There are several technology alternatives for "last mile" wireless connectivity, such as mobile cellular (2G/3G) systems, IEEE 802.16 (WiMAX) and IEEE 802.11 (WiFi) extensions. While mobile cellular (mostly 2G, and some 3G) system deployments in rural India are picking up due to the rapidly dropping cost of equipment, the focus is only on voice service because of better revenue from this service and because the systems are mostly not broadband. WiMAX [6] and other emerging broadband wireless standards hold much promise, but the cost of infrastructure and even terminals will drop to affordable levels for rural India only after several years, when they become mass-market products, as has been the case with 2G cellular technologies.

Systems based on WiFi and its extensions meet the cost target for rural applications. However, WiFi is basically a LAN technology optimized for short-distance communications. Experiments with off-the-shelf equipment have demonstrated the feasibility of using WiFi for long-distance rural point-to-point links as well [4]. However, the DCF MAC of WiFi is not suited for a wide-area distribution service that needs to maximize capacity for subscribers and maintain quality of service [2]. It has also a better performing PCF mode, which is not widely supported. However, both the MACs become very inefficient when the spectrum is re-used in multiple sectors of a BTS site. Fundamentally, when uplink (or downlink) transmissions take place from colocated transceivers in different sectors, in the same band and in a time-multiplexed manner, the uplink (and, similarly, downlink) transmissions of all the sectors *must be synchronized*. Otherwise the receivers in one sector will be saturated by the emissions in another. Further, this synchronization must be achieved with minimal wastage of system capacity due to uplink/downlink turnaround and due to varying traffic characteristics. It is thus clear that a different MAC is needed. Fortunately, some WiFi chips are so designed that they can be easily modified to bypass the internal MAC and obtain the necessary interfaces to the PHY section from an external processor, aided by some simple "glue logic". The authors are currently collaborating with one chip design house to modify a WiFi chip in this manner to implement WiFiRe. Later, depending on economic viability, the MAC may be ported on the on-board processor as well, for use in the subscriber-side equipment. The two-chip solution is expected to lead to significantly less expensive base stations and even user terminals, for several years, when compared to systems based on emerging standards. This will last until chipsets for one or more of these emerging standards become mass-market products. See [5] for an example of a broadband wireless system, developed with a similar approach, that is based on DECT, another low-cost standard.

The attraction of WiFi technology is the delicensing of spectrum for it in many countries, including India. The spectrum allotted in India for WiFi in the 2.4-2.485 MHz band can be employed by anyone for indoor and outdoor emissions without a prior license, provided certain emission limits are met.[2] If the emissions interfere with any licensed user of spectrum in the vicinity, the unlicensed user may have to discontinue operations. Permission for a higher EIRP and higher antenna deployment in rural areas will be required for WiFiRe. These relaxations may be given only for one specified carrier per operator, and it is suggested that a maximum of two operators may be permitted in an area. The Centre of Excellence in Wireless Technology, India, (www.cewit.org.in) is standardizing WiFiRe for deployment in rural India and possibly other countries with a similar need.

IV. THE WIFIRE SYSTEM

A. System Architecture

WiFiRe adopts a star network topology using directional antennas. As shown in Figure 1, a WiFiRe system S consists of a set of Base Stations (BSs), each

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[1] Most calls will be local, charged at around US$ 0.005 per minute. Assuming an average of approximately 3 minutes per day talk-time per household, given the low affordability, the average monthly spend on voice calls per household will be US$ 0.50. At 125 households on the average per kiosk, the average monthly earnings from voice service per kiosk will be around US$ 65 - a significant fraction of anticipated kiosk income.

[2] The maximum emitted power can be 1W in a 10 MHz (or higher) bandwidth, and the maximum EIRP (effective isotropic radiated power) can be 4W and the outdoor antenna can be no higher than 5 m above the rooftop, while the 5 GHz band can be used in India only for indoor emissions (see www.dotindia.com/wpc).

with a sectorized antenna, mounted on a transmission tower at a height of 40 meters for enabling line-of-sight communication. Typically a system is designed to cover a *cell* with a radius between 15 km and 20 km. WiFiRe has a link layer that provides long-distance reliable connections, and supports service guarantees for real-time and non-real-time applications. The Subscriber Terminal (ST) antenna, mounted at around 10 meters height, is directional, which minimizes cochannel interference to neighboring cells. Because of this, and because of obstructions due to terrain variation over large distances, we assume that interference into a cell from neighboring cells is negligible. The association between an ST and a System S is static and is preconfigured at the ST. The association of an ST with a BS in a system S occurs at power-on; automatic initialization, ranging and registration procedures associate the ST with one and only one BS.

Figure 2 depicts the network context in which a WiFiRe system is deployed.

B. Sectorization and Frame Structure

1) Overview and Sectorization: Downlink transmissions in one sector will in general interfere with those in neighboring sectors. An appropriate scheduling mechanism controlling transmissions from each BS and ST is therefore required. As a result, a WiFiRe system has a *single* medium access (MAC) controller common to all the BSs to coordinate the medium access among them. For multiple access, WiFiRe employs a time-division-duplexed, multisector TDM (TDD-MSTDM) scheduling of slots. The scheduling is done so as to maximize simultaneous transmission in multiple sectors while keeping mutual cochannel interference within limits. The single MAC is implemented on a processor with support of digital firmware, and among other things, it ensures that all BSs of one System S transmit/receive at the same time.

As shown in Figure 3, time is divided into frames. Each frame is further partitioned into a downlink (DL) and an uplink (UL) segment, which need not be of equal durations. Within each segment there are multiple slots of equal duration. The schedule lets multiple BSs and multiple STs transmit in a downlink slot and an uplink slot, respectively, depending on the mutual interference (see Section V-A).

The WiFiRe MAC service primitives and mechanisms for data/control plane functionality are derived from that of IEEE 802.16 (WiMAX) [6]. Some key aspects of WiFiRe are: (i) The MAC uses the IEEE 802.11 (WiFi) [7] PHY as the physical layer. (ii) The MAC caters explicitly to multisector operation and controls multiple colocated IEEE 802.11 PHYs, one for each BS. (iii) The MAC assumes that only a single channel is shared among the IEEE 802.11 PHYs. Hence it has a novel TDD-based mechanism for intereference-free transmission and reception in the system.

2) Physical Frame Structure: The slot and frame durations are fixed assuming that a single Voice-over-IP (VoIP) packet is approximately 40 bytes in size, and is generated periodically (typically once every 20 or 30 milliseconds) for active connections. Therefore, the frame duration is chosen as 10 milliseconds (this could be 5 milliseconds too) and the slot duration as 32 microseconds. At 11 Mbps, one slot corresponds to 44 bytes; at 2 Mbps, this is 8 bytes. The PHY overhead at 1 Mbps is 6 slots (192 microseconds) and 3 slots at 2 or 11 Mbps (96 microseconds). All transmissions, therefore, are at least four slots in duration (3 for the PHY overhead + 1). A frame has 312.5 slots. This is partitioned between the downlink (DL) and uplink (UL), and the ratio (2:1 being a reasonable default; see Section VII) is to be fixed at the time of system initialization. As shown in Figure 3, 4.5 slots are used as guard time between the DL and the UL, to account for propagation delays and to provide for transmitter-receiver turn-around at the farthest ST. This gives a maximum possible range of about 22 kms.

The DL segment of each frame begins with every BS transmitting a *beacon* block, containing system information (Operator, System and BS IDs), the DL and UL slot allocations (DL-MAP, UL-MAP) for the STs served by it, and control information. The DL sub-frame provides for upto three beacons in order to enable BSs from neighboring sectors to transmit them without mutual interference. Beacons are recommended to be transmitted at 2 Mbps since they contain vital broadcast information.

All downlinks, excluding the beacon, are at 11 Mbps. Since the DL is point-to-multipoint within each sector, (i) multiple MAC PDU(s), and (ii) MAC PDU(s) for different STs, can be combined and transmitted using a single PHY overhead. This is called a *Downlink Transport Block* (DL-TB). The DL-MAP specifies the ST-IDs of the STs for which there are packets in the current DL sub-frame. The MAC header specifies how one or more ST(s) extract one or more IP packets from the DL-TB payload.

All uplinks are also at 11 Mbps. Since the UL is point-to-point within each sector, multiple MAC PDU(s) at a given ST can be combined and transmitted using a single PHY overhead. This is called a *Uplink Transport Block* (UL-TB). The UL-MAP specifies the <ST-ID, Slot No> mapping indicating which ST is to transmit in which slot. The MAC header specifies how the BS extracts one or more IP packets from the UL-TB payload. The key difference between an UL-TB and a DL-TB is that an UL-TB is always for one ST whereas a DL-TB can be for multiple STs in the same sector.

The start of the UL subframe for a BS may optionally have a *ranging block*. This is specified by a bit in the beacon. Each ranging block is of size 8 slots (3 slots for PHY overhead + 1 slot for the ranging request + 4 slots guard time).

The end of the UL subframe may have optional *contention blocks*, indicated by an ST-ID of all 0's in the UL-MAP. Contention blocks are used to transmit registration request messages, resource reservation messages and data for best-effort connections. In case two ST(s) transmit in the same contention block, the packets are lost due to collision. Each ST infers a collision when the appropriate response timer expires.

The sequence of various blocks in the frame for one BS is shown in Figure 4.

C. MAC Services

The WiFiRe MAC is *connection-oriented*, along the lines of IEEE 802.16 [6]. A *connection* defines the mapping between peer data link processes that utilize both the MAC and QoS class definition. Each ST has a 48-bit universal MAC address, and a connection is identified by a 16-bit Connection Identifier (CID). For link resource allocation, a system S may grant bandwidth to an ST in one or more of the following ways: (i) Unsolicited bandwidth grants, (ii) Polling (real and non-real time), and (iii) Contention Procedures. The link protocol includes mechanisms that allow an ST to transmit resource (slot) reservation requests to S, for the UL and DL segments. This enables an ST to request for specific delay and bandwidth guarantees. Upon receipt of such resource reservation requests, the MAC layer at S executes a scheduling functionality that tries to meet the demands of the ST(s) for the next time frame. This link schedule information is captured as the DL-MAP and the UL-MAP and transmitted with the corresponding beacon.

The MAC layer provides interfaces for dynamic addition, modification, and deletion of connections. Also, within a scheduling interval, bandwidth may be granted by S on a per-connection basis (Grant Per Connection), or as an aggregate of grants for each service flow category (Grant Per Service Flow), or as an aggregate of all grants for an ST (Grant Per Subscriber Terminal).

D. MAC Protocol Phases

The WiFiRe MAC protocol can be divided into two major phases: 1) Network Entry and Initialization (with two sub phases: Ranging and Registration), and 2) Connection Management and Data Transport. The actions in each phase are mostly adaptations of the corresponding actions in IEEE 802.16 [6]. We summarize them below.

1) Network Entry and Initialization:

a) Ranging and Timing Advance: An ST, upon powering up, listens for one or more beacons for the configured Operator ID and System ID. Using the beacon arrival timing from the PHY, the ST also synchronizes its local frame clock. The ST then forms a *Ranging Request* message and sends it in the ranging block of the UL subframe, for each BS that it hears. Informally, the Ranging Request has the following information: System ID, ST ID, BS ID(s), and signal strengths of all the BS(s) that are audible to the ST.

Thereafter, the ST waits and monitors the DL-MAP in *all* beacons of the subsequent frames. If no response is received within a timeout period, the ST sends the Ranging Request again after a random back-off time period. S receives the ranging request message via one or more BSs, selects the BS to associate the ST with, and determines the *Timing Advance* to be used by the ST to be slot synchronized with the system frame clock. The Timing Advance is obtained by measuring the arrival time of the Ranging Request message with respect to the start of the ranging slot block at the BS.

The system S next constructs a *Ranging Response* message, puts it in the transmit queue of the corresponding BS, and invokes the scheduler. The scheduler (asynchronously) includes it in the DL-MAP of a subsequent frame. The scheduler may (optionally) simultaneously provide an UL slot allocation (in the UL-MAP) for the registration request transmission by the ST.

From the Ranging Response message, the ST determines the Timing Advance for its start of UL subframe, the *Basic* CID, and the *Primary* CID to be used for further exchanges. The Basic CID is for periodic ranging and the Primary CID is for further exchange of management messages. The Ranging Response may optionally recommend the transmitter power level to be used by the ST. This facilitates power control and better reuse across sectors (see Section V-A).

b) Registration: After ranging, the ST enters the registration phase in order to acquire an IP address. The ST transmits the *Registration Request* message in the allocated UL slots (if any) or in UL contention slots, and waits for a registration response. The ST retransmits this message after a random back-off if no response is received within a timeout period. The system S receives the Registration Request and after authentication, assigns an IP address to the ST via a *Registration Response* message in the DL subframe. The Primary CID is employed by the ST for these messages.

2) Connection Management and Data Transport: This procedure enables the ST to create, maintain and terminate a connection, with the desired QoS parameters. When the higher layer at the ST initiates a data communication, the ST sends a *Dynamic Service Addition Request* message to S, in the appropriate UL slot. Upon receipt of the message, S assigns a data CID and responds with a *Dynamic Service Response* message, containing the associated QoS parameters. Thereafter, this CID is used for data transport. As in IEEE 802.16, resources are granted as per the following criteria:

1) If it is an *Unsolicited Grants Service* (UGS) flow, the scheduler at S assigns a periodic bandwidth grant in the UL subframe to the ST.
2) If it is a *real-time Polling Service* (rtPS) or a *non-real-time Polling Service* (nrtPS) flow, the ST requests bandwidth whenever required by sending an appropriate *Dynamic Service Change Request* message. Subsequently it transmits the data in the assigned slots. The rtPS service offers real-time, periodic, unicast request opportunities, which meet the real-time needs of the flow, and allows the ST to specify the size of the desired grant. This service has a higher request overhead than UGS, but supports variable grant sizes for optimum data transport efficiency. The BS needs to provide periodic unicast request opportunities. The key service information elements are the *Nominal Polling Interval*, the *Tolerated Poll Jitter*, and the *Request/Transmission Policy*. The nrtPS is designed to support non-real-time flows that require variable size data grant slots on a regular basis, such as high-bandwidth FTP. The service offers unicast polls on a regular basis, which ensures that the flow receives request opportunities even during network congestion.
3) If it is a *Best Effort Service* (BES), then the ST is allowed to use contention request opportunities available at the end of each frame.

The Connection Management Procedure also allows for transmission of a *Dynamic Service Deletion* message by the ST to terminate a connection. As in WiMax, the WiFiRe MAC supports an optional retransmission mechanism in the form of a a window-based ARQ, with selective-ACK.

V. SINGLE CHANNEL MULTISECTOR TDD MAC

The scheduling problem can be described as follows. There are n sectors (e.g., $n = 6$), each with its BS. There are m STs (e.g., $m = 60$), each associated with a BS. This association of the n BSs and the m STs forms a bipartite graph. The scheduling frame, of length N slots (e.g., 300 slots), is partitioned into N_D (contiguous) downlink slots (e.g., 200 slots), and N_U uplink slots (e.g., 100 slots). During each slot time a schedule comprises a matching (i.e., a set of simultaneous uplink (or downlink) transmissions) on the above bipartite graph. However, not all matchings are feasible, since transmissions in a sector can interfere with links near the boundaries of the neighbouring sectors (see [8]). These *interference constraints* are governed by the radiation pattern of the BS antennas.

The scheduling problem is then the following: for each of the N slots in each frame, determine a feasible matching so that the QoS objectives of various traffic flows being carried are met, and the system capacity is maximised. Some of the objectives emanating from this statement are listed next: (i) The matchings chosen should be maximal (i.e., no additional transmissions can be added), subject to the interference constraints. (ii) Since voice packets are sensitive to delay and loss, they should be scheduled with priority, and should be subject to admission control. (iii) Each transmission burst is associated with a substantial (e.g., 3 slots) PHY overhead. Hence, as much data as possible should be transmitted once a burst starts. This requires combining voice and data slots into bursts, and, in downlink bursts, combining transmissions to multiple STs. (iv) An attempt should be made to provide fair throughput across the elastic data transfer flows. In this section we show how these objectives are addressed via a simple heuristic scheduler; we also provide simulation results that demonstrate the system performance that is achieved.

A. Optimal Spatial Reuse

In this section we consider the problem of finding the maximum number of simultaneous transmissions possible in different sectors in the uplink and the downlink. As argued in Section IV-A, we consider only an isolated WiFiRe cell, and hence we model only intracell interference. There is no power control in the downlink. The BSs transmits to all the STs at the same power. There is static power control in the uplink. Each ST transmits to its BS at a fixed power, such that the power received from different STs at the BSs are nearly the same. The STs near the BSs transmit at a lower power and the ones farther away transmit at a higher power.

A typical BS antenna pattern is shown in Figure 5. Based on the antenna pattern, one can divide the region into an *association region*, a *taboo region* and a *limited interference region* with respect to each BS. The radial zone over which the directional gain of the antenna is above -3 dB is called the association region. In our analysis, the directional gain is assumed to be constant over this region. Any ST which falls in this region of a BS antenna j is associated to the BS j. The region on either side of the association region where the directional gain is between -3 dB and -15 dB is called the taboo region. Any ST in this region of BS j causes significant interference to the transmissions occuring in Sector j, and vice versa. When a transmission is occuring in Sector j, no transmission is allowed in this region.

In the limited interference region the directional gain of the BS antenna is below -15 dB. A single transmission in this region of BS j may not cause sufficient interference to the transmission in Sector j. But, multiple such transmissions may cause the SINR of a transmission in Sector j to fall below the threshold required for error-free transmission. This is taken care of by limiting the total number of simultaneous transmissions in the system.

In the uplink, there is static power control. We obtain the optimal number of simultaneous transmissions, n_0, as follows. Suppose P_0 is the minimum SINR required at the BS. Using the nominal transmit power P_t, a path loss factor η, and assuming no cochannel interference, the transmitting ST can be at a maximum distance, say, R_0. To allow spatial reuse, the coverage of the system needs to be reduced to $R < R_0$. There is thus a tradeoff between spatial reuse and coverage, which is captured by the spatial capacity measure $C = n_0 R^2$, which has units slots × km^2. We note that this measure has the same motivation as the *bit metres per second* measure introduced in [9]. For each η, there is an optimal n_0 and R such that C is maximum. Shadowing is also incorporated into our analysis, yielding a coverage with, say, 99% probability. We find that (see [10]), for shadowing standard deviation of 8 dB, and for the above described antenna pattern, and a path loss exponent of 2.3 to 4, the optimal spatial reuse ranges from 3 to 4. Following a similar approach, we get the same results for the downlink.

VI. VOICE AND DATA SCHEDULING

A. Greedy Heuristic Scheduler

The theoretically optimal approach is the solution of a constrained dynamic program, which is intractable due to state space explosion. As a simple heuristic, we employ a greedy algorithm for obtaining a maximal weighted matching, with the weights being voice packet queue lengths. A voice packet is assumed to fit into one slot. Consider first uplink voice transmission. The STs are scheduled such that the one with the longest voice queue is scheduled first. Next, a noninterfering ST with the longest queue is included, and so on until the number of STs in the activation set is equal to the number of simultaneous transmissions possible (i.e., n_0) or until the activation set is maximal. This maximal activation vector is used until one of the STs in the set completes its voice transmissions. Then we remove that ST from the set and schedule another ST, that does not interfere with the STs remaining in the set. The procedure is continued until all the STs complete transmitting their voice packets. The frame now contains only voice packets and several slots might still be unused. These remaining slots are used to pack in TCP transmissions. If anywhere in the schedule during voice transmission, a situation occurs where there are no more noninterfering STs in a sector that can transmit voice, but there is one that can transmit data, then data is scheduled for that ST. In the downlink, the approach is similar, except that packets to different STs can occupy the same transmission burst in a sector, so that the PHY overhead is reduced.

B. Fair Scheduling for Data Flows

To minimise the effect of PHY overheads, voice and TCP slots are combined into transmission blocks. To provide fairness between data transfers, we keep track of the average rates allocated to the STs over time. The STs with low average rates over the past frames are given a chance to transmit first. In each frame, maximal matchings are formed starting from the ST with the lowest average rate. Let $\mathbf{R}_k$ be the vector of average rates allocated to STs up to (and including) the $k-1$th frame, and $\mathbf{r}_k$ be the vector of rates allocated to the STs in the kth frame, i.e, the fraction of slots allocated to STs in the kth frame. The average rate achieved by the STs is obtained by exponentially weighted averaging: $\mathbf{R}_{k+1} = \alpha \mathbf{R}_k + (1-\alpha)\mathbf{r}_k$. We find the maximal matchings as in the greedy heuristic scheduler, with the difference being that the links are chosen according to the average rates as described above.

VII. VOICE AND DATA CAPACITY: SIMULATION RESULTS

The scheduling algorithm discussed in Section VI was implemented in a MATLAB simulation. The PHY rate is 11 Mbps. We consider a random distribution of 80 STs in 6 sectors. The STs are statically associated with the BSs, and their uplink powers are set as described earlier. The spatial reuse n_0 is either 3 or 4, and the taboo regions in each sector, on either side of the sector, are $\theta = 10^\circ, 20^\circ, 30^\circ$. This, along with the static allocation of the STs to the BSs, yields the sets of links that

		Number of voice calls per station		
n_0, θ		1	2	3
3, 10°	min d/l rate	164	148	134
	max d/l rate	178	182	167
	sum d/l rate	13749	12852	11690
	min u/l rate	17.1	8.1	0
	max u/l rate	85	59	34
	sum u/l rate	3570	2286	1229
	packet drop u/l	0	0.0029	0.0229
3, 20°	min d/l rate	163	151	136
	max d/l rate	179	173	177
	sum d/l rate	13545	12798	11799
	min u/l rate	13	5	0
	max u/l rate	88	57	31
	sum u/l rate	3510	2285	1110
	packet drop u/l	0	0.0033	0.0312
3, 30°	min d/l rate	167	153	137
	max d/l rate	180	173	161
	sum d/l rate	13883	13000	11750
	min u/l rate	16	5	0
	max u/l rate	83	62	43
	sum u/l rate	3463	2114	1176
	packet drop u/l	0	0.0042	0.0346
4, 10°	min d/l rate	224	204	190
	max d/l rate	294	278	258
	sum d/l rate	19807	18377	17007
	min u/l rate	38	18	0
	max u/l rate	106	92	78
	sum u/l rate	5161	3776	2906
	packet drop u/l	0	0.0029	0.0283
4, 20°	min d/l rate	204	194	177
	max d/l rate	283	255	274
	sum d/l rate	19312	17919	16430
	min u/l rate	25	9	0
	max u/l rate	157	168	160
	sum u/l rate	4833	3699	2771
	packet drop u/l	0	0.0025	0.0304
4, 30°	min d/l rate	172	165	140
	max d/l rate	212	208	190
	sum d/l rate	15573	14078	12499
	min u/l rate	15	7	0
	max u/l rate	92	70	53
	sum u/l rate	3468	2400	1359
	packet drop u/l	0	0.0029	0.0354

TABLE I

SIMULATION RESULTS FOR 80 STS IN 6 SECTORS, AVERAGED OVER 30 RANDOM DEPLOYMENTS. THE TABLE ENTRIES ARE THE DATA THROUGPUTS, IN KILO BITS PER SECOND.

can be scheduled together (i.e., the feasible matchings). Note that a smaller value of θ implies better quality antennas. All STs have the same number of ongoing voice calls: 1, 2 or 3. One VoIP call requires one slot every alternate frame. A voice packet that arrives in the system is scheduled within the next two frames. If the scheduling constraints do not allow the voice packet to be transmitted within two frame times of arrival, the packet is dropped. In the simulation, we have assumed synchronous arrival of voice packets, i.e., if two voice calls are going on from an ST, packets for both calls arrive synchronously, in the same frame. This assumption can be expected to provide a worst case scenario, and was also easier to handle in our Matlab simulation. The data traffic model is such that all the STs have packets to be transmitted throughout.

The results are shown in Table I, in which the entries are the *data* throughputs in kilo bits per second. Further, *min d/l rate* is the average of the minimum rate over STs in the downlink, averaged over 30 random deployments; *max d/l rate* is the average of the maximum rate over STs in the downlink, and *sum d/l rate* is the average of the sum of downlink rates to the STs. If *sum d/l rate* is divided by the number of STs then we obtain the average rate per ST, while the *max d/l rate* and the *min d/l rate* provide a measure of the variability around the mean rate. The same measures are also given for the uplink. The *packet drop u/l* is the fraction of voice packets dropped in the uplink, this being the bottleneck direction. All the rates indicated in Table I are in terms of the MAC payload. The PHY overhead has already been accounted for in the calculations.

Each voice call requires a payload of 44 Bytes every 20 ms, and hence 1.41 Mbps are utilised per voice call, in the uplink and downlink, for 80 STs. With a PHY rate of 11 Mbps, with $n_0 = 3$ we have an aggregate nominal rate of 22 Mbps in the downlink and 11 Mbps in the uplink (assuming that $\frac{2}{3}$ of the frame time is allocated to the downlink). From the table, it can be seen that with 80 STs in 6 sectors, and 1 voice call, with a taboo region of 10° on either side of each sector, and $n_0 = 3$, each ST gets an average minimum data throughput of 164 Kbps, and the average total rate is 13.749 Mbps. Adding to this 1.41 Mbps, we obtain about 15.16 Mbps, for a nominal downlink bandwidth of 22 Mbps. The difference is because of PHY overheads, and the inability to fill up all slots in a frame. We notice that a second simultaneous call at each ST reduces the data throughput by less than 1 Mbps; this is because the packing can become more efficient. For this same case, with one voice call, the average minimum uplink data throughput is 17 kbps, and the average total downlink data throughput is 3.57 Mbps. Adding to this 1.41 Mbps for voice, we obtain a total uplink utilisation of 5.18 Mbps over a nominal bandwidth of 11 Mbps allocated to the uplink. Being smaller, the uplink frame is more inefficiently packed. We observe, from the large difference between the values of the min u/l rate and max u/l rate, that there is much larger variability across STs in the data throughput obtained in the uplink than in the downlink.

When $n_0 = 3$ and the taboo region has an angular width $\theta = 10°$, the fraction of voice packets dropped is 0.29% when 2 calls are supported per ST, and 2.29% when 3 calls are supported per ST. With 3 voice calls per station, we can see that the packet drop probability is high, and the uplink capacities to some STs are 0. With $n_0 = 3$, the width of the taboo region does not have an effect on the system capacity, since it is always possible to schedule in 3 sectors. With $n_0 = 4$, the system capacity reduces as θ increases (i.e., the antennas are made less directional). With $\theta = 30°$, we can usually schedule transmissions in just 3 sectors in a slot, even though the SINR constraints allows 4 transmissions in a slot.

VIII. CONCLUSION

We have motivated and defined WiFiRe, a new system for rural broadband voice and data access, based on the WiFi PHY, and a new single channel multisector TDM MAC using directional antennas. For a typical BS antenna pattern, we found that a spatial reuse of 3 or 4 is optimal. Then, we used a simple heuristic greedy scheduler to assess the voice and data capacity of the system. We concluded that a spatial reuse of 4 requires higher quality antennas at the BS in order to gain a capacity advantage. With an 11 Mbps PHY, 80 STs, a spatial reuse of 3, a TDD downlink-uplink ratio of 2:1, and one voice call simultaneously ongoing at every ST, we found that the aggregate data capacity was about 13.75 Mbps in the downlink and about 3.5 Mbps in the uplink. A significant drain on capacity is the PHY overhead in IEEE 802.11 for a VoIP packet, which is three times the payload. By virtue of being able to combine payloads in the downlink and better packing efficiency, a second simultaneous call at every ST reduces the downlink data throughput by less than 1 Mbps.

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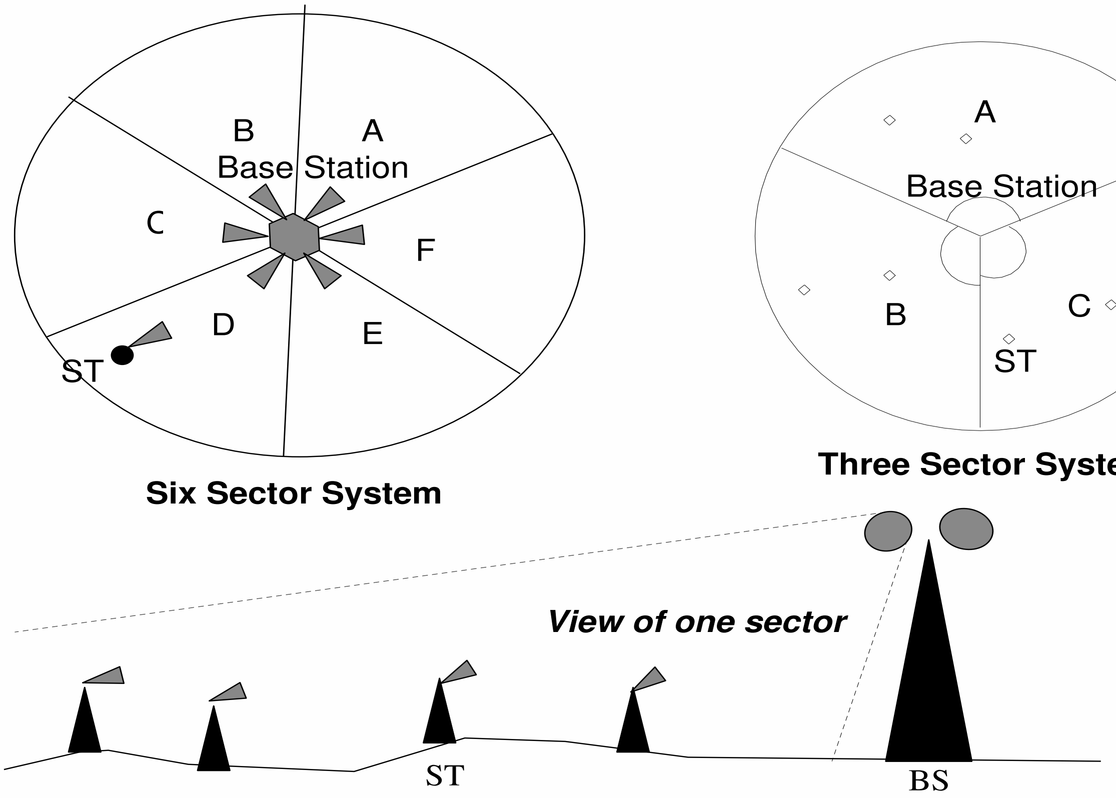

Fig. 1. WiFiRe network configuration. Two different sectorisations are shown on the top. The bottom diagram shows a tall tower carrying several BSs, with sector antennas, and several STs in a sector, with lower height directional antennas.

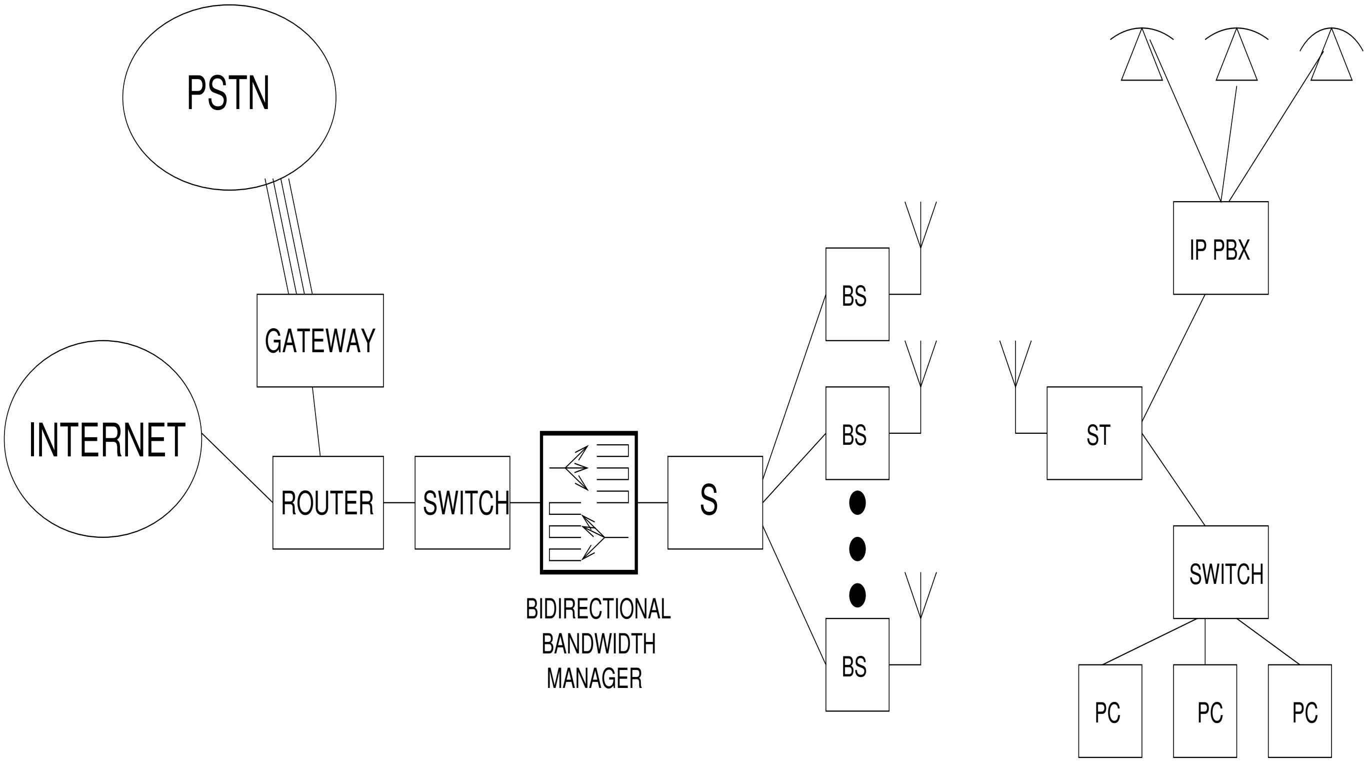

Fig. 2. The WiFiRe system as a part of an overall network architecture. An optional bandwidth manager is also shown.

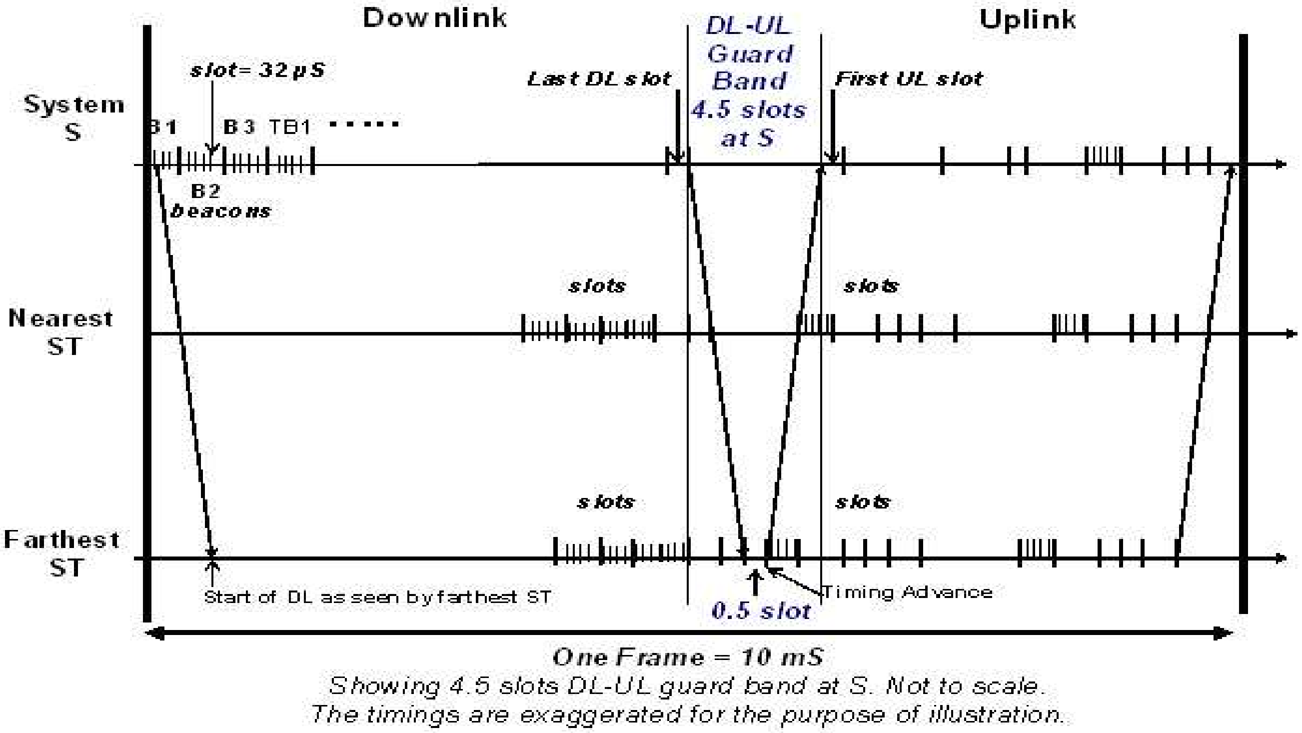

Fig. 3. WiFiRe uplink-downlink frame timing.

Fig. 4. The sequence of slots seen by each BS.

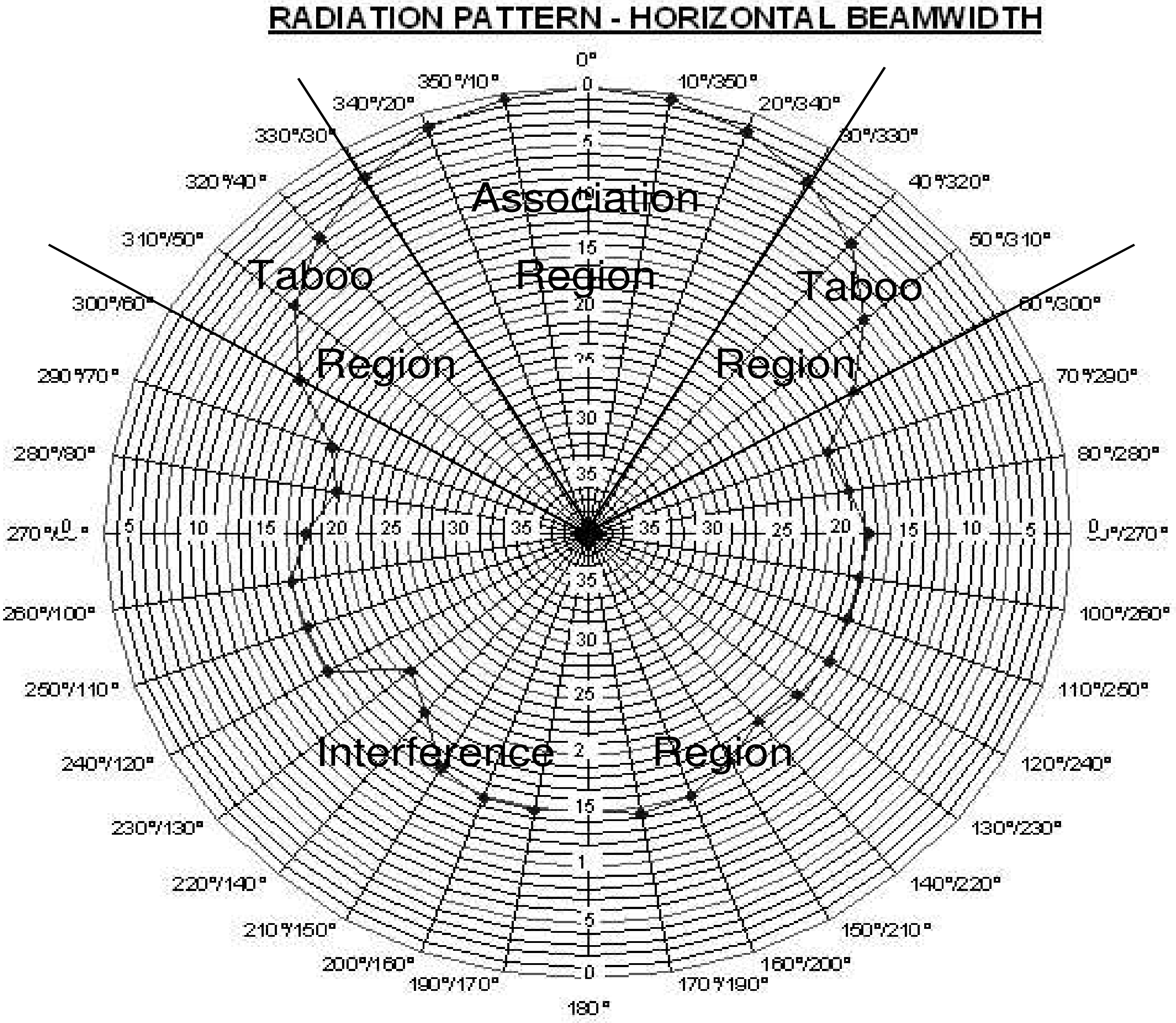

Fig. 5. Radiation pattern of a typical BS antenna that could be used in the deployment. The association region is a 60° sector centered at the 0° mark, the taboo region is 30° on either side of this association region, and the limited interference region covers the remaining 240°.