Dynamic Time Slot Partitioning for Multimedia Transmission in Two-Hop Cellular Networks

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Abstract—In recent years, there has been an exponential increase in the number of mobile phone users. In addition, a significant growth in the demand for high-rate multimedia services over wireless networks, such as video conferencing, multimedia streaming, etc., was noted. Different solutions were proposed to support high quality high data-rate delivery to mobile users, including resource allocation techniques for packet radio-based next generation cellular networks. In this paper, an efficient time slot allocation method - *Dynamic Time Slot Partitioning (DTSP) algorithm* based on *statistical multiplexing* is proposed for a two-hop cellular architecture. In DTSP, the available bandwidth resources are increased by partitioning each time slot into several minislots; different number of minislots are allocated to different users. The DTSP algorithm is based on asynchronous time division multiplexing, wherein users with variable number of packets in their buffers can transmit data sequentially without any loss in the overall available resources.

The key advantage of DTSP is that it can flexibly adapt to different quality of service requirements, especially when combined with adaptive modulation. It has been observed that the system capacity achieved by the DTSP algorithm in the downlink mode using adaptive modulation is up to 41% higher than when existing solutions are employed. In addition, DTSP results in significantly lower time for data transmission than the state-of-the-art region and time partitioning techniques.

Keywords: adaptive modulation, cluster-based design, dynamic time slot partitioning, statistical multiplexing, time division multiple access, two-hop.

1 Introduction

The wireless industry is experiencing a great revolution in order to meet the expectations of the end users. The users today expect services such as video conferencing, fast movie download, multimedia streaming, video-on-demand, etc. on their wireless devices, even while on the move [1]. However, there are two major technological bottlenecks that hinder such deployment in cellular networks: the power constraint of the transmitting device, and the transmission distance between the transmitter and receiver. In a traditional single-hop cellular network, the distance between the base station (BS) and the mobile station (MS) is in the range of several kilometers (km). Wireless terminals are energy constrained devices. Hence, the transmitter power cannot be increased indiscriminately in order to support very good quality high data-rate. Therefore, an efficient alternative method for high data-rate communication involving battery-constrained wireless devices is to use a multihop architecture.

In the multihop architecture for cellular communications, the source and destination nodes communicate with each other over multiple hops [2]. Different algorithms and architectures have been proposed over the recent years for efficient spectrum and resource utilization in multihop cellular networks [3], [4]. An integrated cellular *ad hoc* relay network has been proposed in [5] that diverts the traffic from highly loaded cells to lightly loaded cells. It has been shown in [6] that in a practical situation, 84% of multihop communication takes place within four hops, with 62% of the communication happening in two hops. Also, as optimum resource allocation in multihop cellular networks is an NP-hard problem [7], the focus has been on resource allocation for two-hop cellular networks [8], [9]. A novel cluster-based design has been recently proposed for two-hop cellular architectures in [10], [11]. The cluster-based design results in a frequency reuse of *one* and is found to be superior in achieving higher system capacity in comparison with the state-of-the-art two-hop algorithms [12].

For multimedia delivery, the downlink traffic is usually much higher than that on the uplink. Theoretically, time division multiple access (TDMA) or frequency division multiple access (FDMA) could be deployed to support multiple users in bidirectional mode. In practice, asymmetric traffic services are efficiently supported by TDMA solutions [13]. TDMA systems (such as GSM, UMTS, etc) have a plurality of time slots in a given time frame. For example, in GSM systems, each TDMA time frame has eight time slots and each time slot is reserved for use by a particular user. In case of time

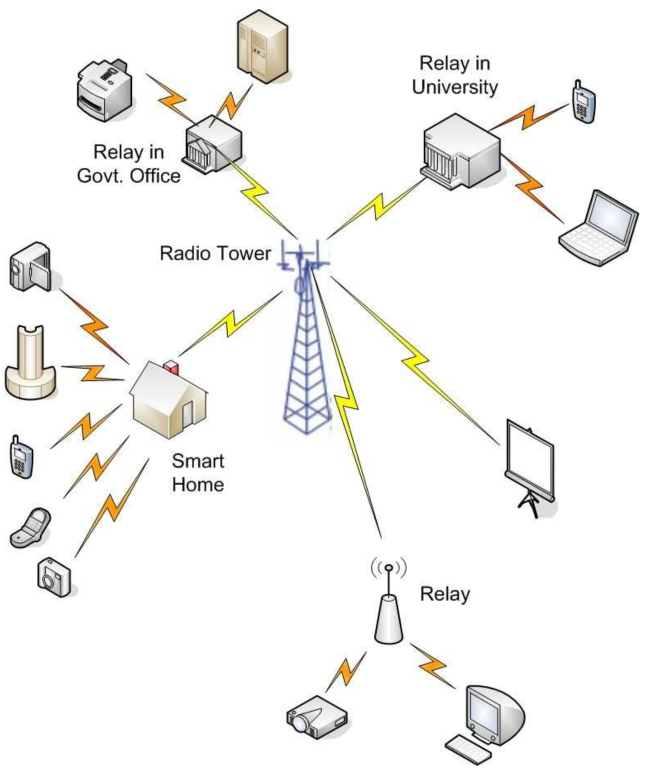

Fig. 1. An example of a next generation multihop cellular architecture

division duplexing (TDD) based UMTS (UTRA-TDD), there is employed the concept of code division multiple access [14]. There are 15 time slots per frame, and each time slot is simultaneously served by many users.

In this paper, a novel and efficient algorithm - *Dynamic Time Slot Partitioning (DTSP)* is proposed for transmitting data with variable packet sizes in two-hop cellular networks. The DTSP algorithm enhances the TDMA scheme by dynamically assigning the time slots to different users depending on the amount of traffic carried by the users. The DTSP algorithm deployed in an asynchronous time division multiplexing (TDM) system enables the users to transmit their data sequentially without any loss in the available resources.

The organization of this paper is as follows: section 2 describes the related works, while section 3 presents the network model of an OFDM (orthogonal frequency division multiplexing) based TDD-TDMA two-hop cellular network. Section 4 explains the DTSP method in detail along with the algorithm for time slot allocation for the different kinds of communicating pairs in both uplink and downlink. The simulation results are provided in section 5 and the conclusions are drawn in section 6.

2 Related Works

Recently, there has been several significant research work on time slot allocation in the dynamic TDD mode [15], [16]. Importantly, considerable research was performed in the area of image and video delivery in wireless networks using OFDM systems [17], [18]. A *maxmin*{signal-to-interference ratio} algorithm was proposed in [20] to maximize the minimum signal to interference ratio experienced by the communicating pairs. However, in case of an asymmetric traffic, there would be cross-time-slot regions between different cells, which would in turn result in high interference across these different cells. In [19], a time slot allocation based on region division (DARD) is proposed wherein each cell is divided into two regions: the inner region and the outer region. In presence of cross-time-slots between the adjacent cells, the BS allocates these cross-time-slot resources to the MSs located in the inner region, whereas the remaining resources are allocated to the outer region. However, DARD only considers co-channel interferences (CCI) from the BSs and excludes those from the MSs in the neighboring cells. Hence, although DARD improves the performance in some situations, it does not always deliver high data-rates, especially when there are high number of users.

A region time partitioning for OFDM-based dynamic TDD (RTP D-TDD) system has been recently proposed in [21] wherein a cell is divided into several regions, and each time slot is divided into several mini slots. Each mini slot is then given to users of different regions. Users in each region exclusively transmit/receive data in the corresponding mini slots, so the CCI in the cross-time-slot region is reduced. However, this time slot allocation method is based on synchronous TDM and is not efficient for next generation all-IP based packet oriented services, especially when the different packets are of varying length. This is primarily because in a synchronous TDM system, all the time slots are of the same duration. Hence, different data traffic with variable packet sizes cannot be served sequentially without any loss of time slot resources, using a fixed time slot division scheme, as in the RTP D-TDD. In a very recent work [22], it has been shown that a substantial throughput gain is achieved in an OFDM based distributed two-hop network. The focus is on diversity schemes using relay nodes, and not on resource allocation techniques. On similar lines, a multihop dynamic channel assignment (mDCA) scheme has been recently proposed for clustered multihop cellular networks [23], which works by assigning channels based on information about interference in surrounding cells.

Cidon and Sidi in their landmark paper [24] discuss centralized algorithms before they move towards distributed solutions for multihop networks. They propose dynamic channel assignment algorithms for multihop packet radio networks where the resource assignment starts from a random node and continues by examining nodes from outside two hops of the selected node. Instead of random picking of nodes, our approach selects the transmitting nodes sequentially based on their arrival in the clusters. Additionally, a significant feature of our work is that it caters to different traffic of each transmitting node. In Cidon and Sidi's paper, the proposed algorithms - *maximum and maximal slot assignment* - are computationally very extensive. In our algorithm, there is no additional computation, which results in a very efficient channel utilization for hierarchical cellular networks (reuse factor of one). In the same context, the paper by Tonguz [25] talks about call blocking probability and load balancing/ sharing, wherein the traffic is diverted from hot cells to cold cells. The load balancing scheme provides a framework for relay-based multi-cellular networks. Accordingly, all new calls will be blocked with probability $p = 1$ if all relay and cellular band channels are used [26]. When the call is over, there is a certain finite time period after which the channel is alloted to other users in neighboring cells. In addition, a recent work [27] has proposed a Petri-net based automated distributed dynamic channel assignment method for the cellular network which improves the call blocking probability. However, in the current paper, the resource allocation focuses on reuse within the same cell which is an important difference from the above mentioned work. In addition, in our proposed scheme, the allocation occurs on the next mini slot/ instant, thereby improving the resource efficiency.

Significantly, there has been considerable research in the cross-layer domain for multihop cellular networks. The concept of cross-layer design is based on the architecture where different layers can exchange information in order to improve the overall network performance [28]. Van der Schaar and Shankar [29] have explained the different challenges and new paradigms in the cross-layer design especially for wireless multimedia delivery. A cross-layer based time division mechanism for wireless networks has been investigated over the recent years [30], [31]. However, none of these cross-layer approaches have proposed any real-time division of the time slots. In this context, it should be noted that in the multimedia transmission framework, the emphasis is not just on the connectivity, but also on the data-rate at which the packets are transferred. Hence, this paper focuses not only on ways to increase the radio resources, but also to dynamically vary the data-rate of the wireless network, addressing the needs of rich-media delivery.

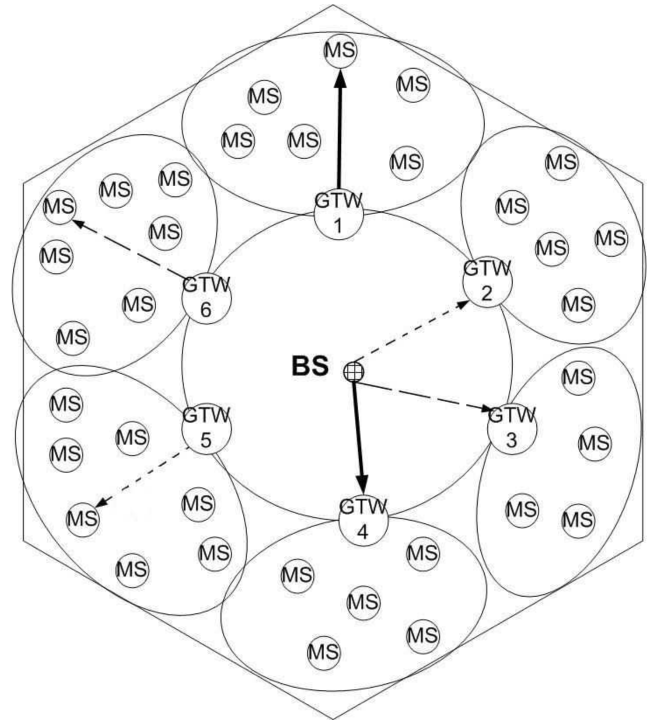

Fig. 2. Multi-cellular architecture with all GTWs in the cell located equidistantly from the BS

3 Network Model

3.1 TDD/TDMA based Two-Hop Network Model

A network model based on multi-cellular architecture is considered wherein there is a center cell surrounded by six cells in the first tier. For each cell, a cluster-based architecture is considered. Fig. 2 illustrates this cluster-based design for one cell. The cell has a BS at the center, and has radius r. Since the network is designed for two-hop, each cell is split into two exclusive regions: an inner and an outer region. The inner region is the circular area around the BS and has a radius, τr, where τ is usually taken as 0.5 [32]. Being close to BS, all MSs in the inner region communicate directly with the BS. For an effective communication, the outer region is divided into several elliptical clusters. An analytical derivation carried out in [32] prove that a maximum system capacity is achieved when the number of clusters in each cell is six. Hence, six clusters per cell are taken into account throughout this work, as shown in Fig. 2. Each MS in the outer region is assigned to one of the clusters and communicates with the BS in two hops, through its designated gateway (GTW). GTWs are either regular MSs or dedicated wireless devices, which act as cluster-heads in the two-hop design. Each MS is assigned a unique ID based on its location (inner region, outer region), its GTW location, and its cluster ID. It should be noted that the cluster-based architecture has evolved from the micro-cellular approach and micro-cells are already deployed in the real-world.

Notably, a TDD/TDMA scheme is considered in the system design. The major advantage of using a TDD system in the two-hop design is that the relays can use the same frequency for both receiving and transmitting the signals. Given the two-hop nature, two different radio resources (two time instants in a TDMA system) are necessary for the MSs in the outer region to communicate with the BS. Hence, as compared to an equivalent single-hop network, every pair in the two-hop model would communicate over only half the time slot period. Additionally, since the cluster-based two-hop design results in a reduction of the transmission distance of all the communicating pairs, the same radio resource could potentially be reused *twice* in every cell. For example, in Fig. 2, the (BS $\rightarrow$ GTW4) pair communicates, while at the same time, the (GTW1 $\rightarrow$ MS) pair that is located diametrically opposite with respect to the BS also communicates (shown in dark thick lines). Similarly, in every other time instants, there are two simultaneously communicating pairs, located within diametrically opposite clusters with respect to the BS. In addition, the same resource is used by two simultaneously communicating pairs in every adjacent cell in the 7-cell scenario. Hence, a frequency reuse ratio of *one* is achieved. The second major advantage of using TDD/TDMA is that the cell specific asymmetric traffic can be easily supported in the cluster-based design, without having any additional interference, from the same-kind of entities (BS to BS, MS to MS and GTW to GTW) [33].

3.2 Network Performance Modeling

The system modeling focuses on the carrier-to-interference ratio (γ) such that γ holds the information about the interferences and power fading. Large scale fading refers to received signal variations with distance [34]. This is particularly significant for an OFDM system with increasing channel bandwidth (100MHz for beyond 3G networks [35]). In terms of interference sources, this paper considers contributions from both own-cell links and other-cell links, termed multiple-access interference and CCI respectively. In order to minimize the effect of interference arising from two simultaneously communicating pairs in every cell, a *Protocol Model* is considered in the network design. Accordingly, if d_c is the transmission distance between a transmitter and receiver, then a circular region of radius (1 + Δ)d_c is defined around every communicating receiver so that, within this region, there is no other transmitter apart from the desired transmitter. Δ is the spatial protection margin, also defined as the exclusion range ratio. Increasing Δ decreases the interference that the receiver might experience. However, it also decreases the number of pairs in the network that can communicate using the same radio resource. In order to optimally trade-off between the amount of interference experienced by each user and the number of simultaneously communicating users, the value of Δ needs to be close to unity [36]. Therefore, a Δ of 1.0 is considered in the hierarchical cluster-based two-hop cellular design.

3.3 OFDM Subcarriers

Let N_c be the total number of subcarriers, and let subcarrier $k \in$ s= $\{\mathrm{a}_1, \mathrm{a}_2, ..., \mathrm{a}_\mathrm{m}\}$, where $a_i \in \{1, 2, ...N_c\}$. s is a set of subcarriers belonging to a single user in cell i, and k does not experience interference from the set of subcarriers [37]. The cardinality of s, $|s|$, is the number of subcarriers per user, which can vary from zero to N_c (total number of subcarriers per BS). The received signal power on subcarrier k in cell i is given by ${R_k}^i$ (expressed in watts) [38]:

$$ {R_k}^i = {P_k}^i {G_k}^i |{H_k}^i|^2 \quad (1) $$

where ${P_k}^i$ is the transmit power on subcarrier k in cell i, ${G_k}^i$ and ${H_k}^i$ are the path gain and channel transfer function respectively between the transceiving wireless devices, for subcarrier k in cell i [39]. The path gain depends mainly on the distance between the transceiving wireless devices ${d_k}^i$, but is also influenced by standard deviation of the lognormal shadowing, ζ, across the transmitter and receiver of the wireless link. In case the channel transfer function is unity, or a constant as in many cases, the received power of the desired receiving node is a function of the transmitted power and the path gain and is given by:

$$ {R_k}^i = {P_k}^i ({d_k}^i)^\alpha {\epsilon_k}^i \quad (2) $$

where ${\epsilon_k}^i$ is the shadowing factor of subcarrier k in cell i. However, it should be noted that in case of a cluster-based two-hop cellular network, the transmission distance is small, and hence, shadowing is much less than that experienced in an equivalent single-hop network.

3.4 Network Capacity

The network capacity expressed in bps/Hz/cell is calculated at the center cell of the 7-cell architecture, by taking into account the interferences from the six adjacent cells.

If ${d_{\mathrm{int\_BS}}}^i$ is the distance of the interfering BSs from cell i, then the total received power from the B interfering BS transmitters is given by:

$$ {R_{Bk}}^i = {P_k}^i ({d_{\mathrm{int\_BS}}}^i)^\alpha {\epsilon_k}^i \quad (3) $$

Similarly, if ${d_{\text{int\_GW}}}^i$ is the distance of the interfering GTWs from cell i; then the total received power from the G interfering GTW transmitters is given by:

$$ {R_{Gk}}^i = {P_k}^i ({d_{\text{int\_GW}}}^i)^{\alpha} {\epsilon_k}^i \tag{4} $$

The carrier-to-interference ${\gamma_k}^i$ experienced by the subcarrier at the MS in the outer layer of cell i is therefore given by:

$$ {\gamma_k}^i = \frac{{R_k}^i}{\sum_{i=0}^{6} {R_{Bk}}^i + \sum_{i=0}^{6} {R_{Gk}}^i} \tag{5} $$

An adaptive modulation is considered in the transmission of data packets. For each ${\gamma_k}^i$, $\bar{\gamma_k}$ is assigned, where $\bar{\gamma_k}$ is the target γ of subcarrier k, such that $\bar{\gamma_k} \leq {\gamma_k}^i$ and $\bar{\gamma_k} \in \{\tilde{\gamma_1} < \tilde{\gamma_2} < ... < \tilde{\gamma_m}\}$, where $\tilde{\gamma_m}$ is the carrier to interference ratio of m^{th} discrete threshold. Further, a number of m discrete transmission rates are available, $r_k \in \{r_1 < r_2 < ... < r_m\}$ depending on the modulation scheme, where each $\bar{\gamma_k}$ corresponds to a particular r_k. If a subcarrier has a high γ, then a high data-rate for the same bit error ratio can be obtained by selecting a higher modulation technique.

In a cluster-based two-hop design, the information is transmitted from the source to destination in two hops which in turn requires two distinct time instants. As a consequence, the Shannon capacity for a single link has to be scaled by a factor of $1/2$. However, in each of the seven cells in the cluster-based design, there are two simultaneously communicating pairs, and depending on the distance of the interfering transmitters the receivers of these two communicating pairs would have different values of γ. Therefore, the system capacity (of only the two-hop links) of a cell at any instant of time is calculated from the Shannon equation as:

$$ C = \frac{1}{2} \sum_{j=1}^{N_l} \log_2(\gamma_j + 1) \tag{6} $$

where N_l represents the number of pairs that communicate simultaneously in the cell. N_l = 2 in case of the cluster-based design.

3.5 Packet Arrival

In 3G and beyond, a packet radio network is considered for transmission of data/information in the wireless cellular network. The number of packets generated at the wireless terminal over a certain period of time is a discrete value. Hence, it could be modeled as a binomial distribution and written as:

$$ P(X = k) = \binom{n}{k} p^k (1-p)^{n-k} \tag{7} $$

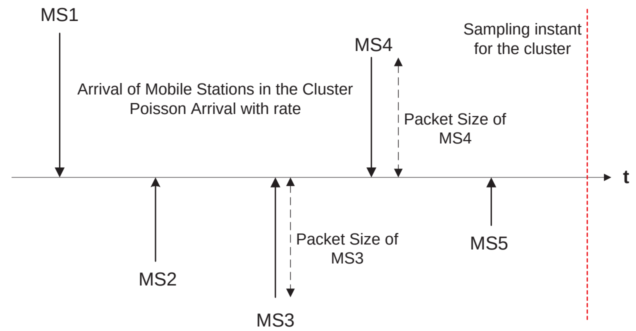

Fig. 3. Sampling instant for determining the buffer size of all MSs

where n is the number of trials, and p is the probability of success of the trial. If λ is taken as the expected value, then p could be written in the limit as: $p = \lambda/n$, according to the law of rare events. This is because, even though the number of packets received by the MS in one unit of time is quite high, the number of users from whom the MS receives the packet is small. Hence, for a large value of n, the binomial probability could be written as:

$$ P = \frac{\lambda^k \exp(-\lambda)}{k!} \tag{8} $$

i.e., the packet arrival is Poisson distributed with mean λ.

In the cluster-based design, the buffer size of all the MSs in a single cluster are measured at a single point of time, as shown in Fig. 3. The data traffic of only these MSs (that are in the same cluster) are considered in the corresponding time frame. Data transmission of any packet that arrives after that particular time instant takes place in the next time frame. Significantly, the GTWs employ a decode and forward technique for relaying the data signals. Hence, the relays decode the symbols, sense the channel for the next hop and then re-modulate the data bits depending on the adaptive modulation technique employed. This provides a flexibility of having different data-rates for different communicating pairs, depending on the γ experienced at each of the receivers.

3.6 Effect of Traffic Asymmetry

In the cluster-based design, the adjacent cells can have different asymmetric traffic (uplink and downlink). Fig. 4 shows a symmetric scenario where all the communicating pairs in the seven cells are in downlink mode. The interference at the GTW node in the center cell is the cumulative effect of the single intra-cell and several inter-cell interferers. In case of an asymmetric traffic, the different cells will have different uplink and downlink modes. Fig. 5 shows the different intra and inter-cell interferences experienced by a MS in case of

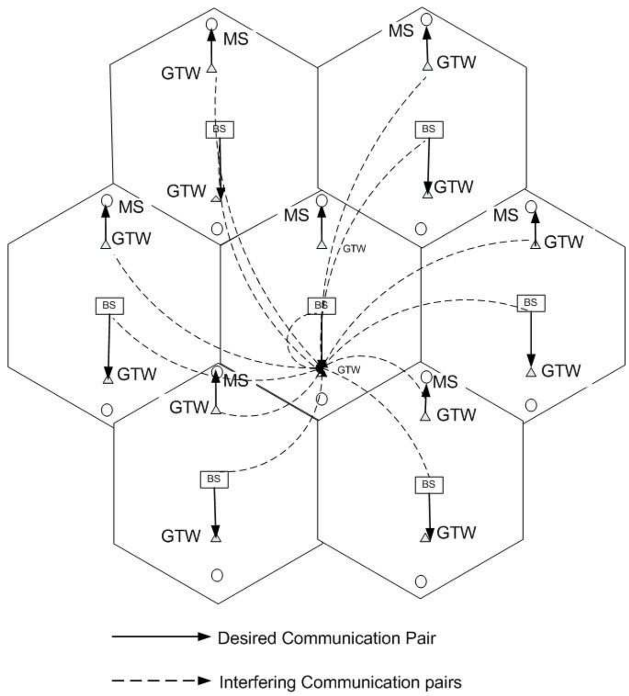

Fig. 4. Intra-cell and inter-cell interference when all communicating pairs are in downlink mode

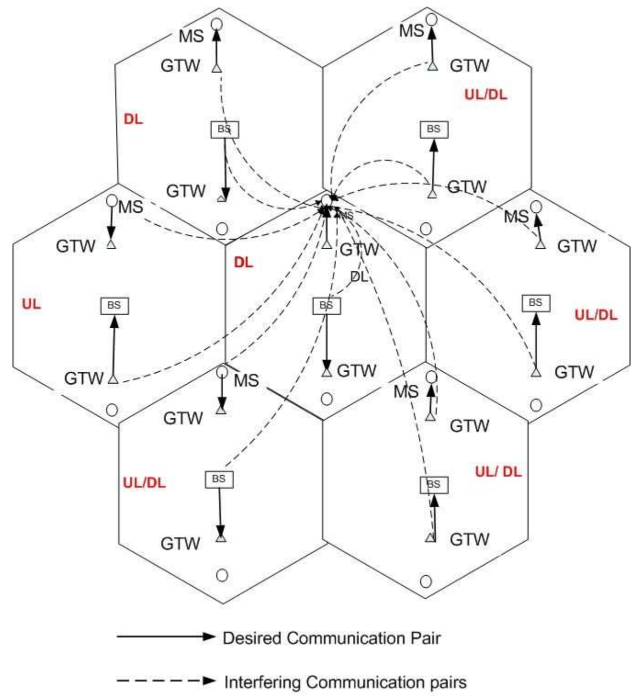

Fig. 5. Intra-cell and inter-cell interference when the communicating pairs are in uplink-downlink (UL/DL) mix mode

an asymmetric traffic between different communicating pairs in the seven-cells. It can be observed that the primary source of interference is still the intra-cell interferer and it adds significantly higher interference than the inter-cell interferers. Hence, the cluster-based architecture and our proposed scheme would function very well even in case of an asymmetric traffic between the different cells, but an increase in the interference will be experienced.

For example, if the two diametrically opposite clusters in the same cell have different asymmetric traffic, the effect of this intra-cell asymmetry is an increase in the interference due to the closer proximity of the interfering transmitter to the desired receiver. A solution for reducing this effect is to have a directional antenna at the transmitters, especially at the BS and relay nodes. In addition, it should be noted that the transmit power of the BS in the practical environment would be significantly higher than that of the relay node, which in turn would be higher than the transmit power of the mobile node. Hence, using a directional antenna or a power-control mechanism (which is more common), the two simultaneously communicating pairs within the same cell can have both different asymmetric traffic and reduced interference.

4 Dynamic Time Slot Partitioning Algorithm

4.1 DTSP Overview

This section introduces the novel DTSP algorithm which combines the benefits of dynamic TDD/TDMA and that of the OFDM design, for efficient communication in multihop cellular networks. An OFDM enhanced TDD/TDMA air interface without an extra FDMA component is considered in the system design. This is justified by the fact that in an asynchronous multipoint-to-point transmission, OFDM-FDMA suffers high multiple access interference due to frequency offsets. The same holds for multihop communication where many uncoordinated simultaneous transmissions exist. In the DTSP algorithm, any time slot could be partitioned into up to a maximum of N mini slots which are given to the same or to different users. User data is transmitted in the mini time slots in a burst format. The number of bits transmitted per mini slot depends on the selected modulation technique, which in turn depends on the γ of the communicating user. Also, the characteristic feature of the DTSP algorithm is that the user who is presently assigned the time slot transmits all its data packets in a single burst. When the particular user finishes transmitting its data packets at the j^{th} minislot in the i^{th} time slot, the next user starts transmitting the data packets in its buffer at the very next mini time slot,

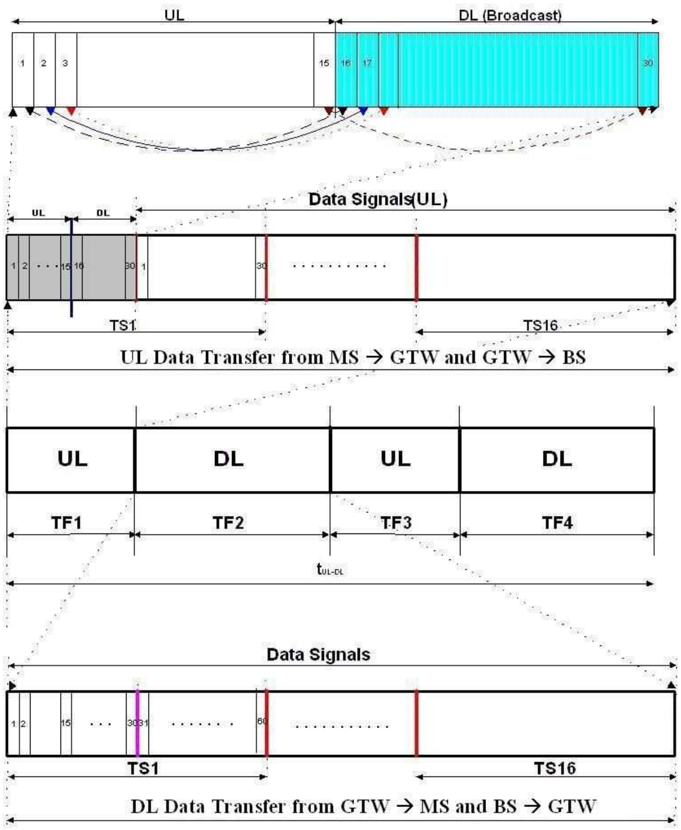

Fig. 6. Time slot allocation in uplink (UL) and downlink (DL)

i.e., at the $(j+1)^{\text{th}}$ minislot in the i^{th} time slot.

The basic principle of DTSP algorithm relies on the statistical multiplexing mechanism that is employed at the MAC layer, for packet-switched transmissions [40]. The DTSP is basically a cross-layer design between the physical layer and the data link layer. DTSP is based on an "on-demand" service rather than on one that preallocates resources for each data stream. Statistical multiplexing-based DTSP algorithm is quite similar to conventional time-division multiplexing (TDM), except that, rather than assigning a data stream to the same recurrent time slot in every TDM frame, each data stream is assigned time slots (of fixed length) that often appear to be scheduled in a randomized order. This results in varying delay, while the delay is fixed in conventional TDM methods. Statistical multiplexing allows the bandwidth to be divided arbitrarily among a variable number of channels, while the number of channels and the channel data-rate are fixed in the conventional TDM [41]. Significantly, statistical multiplexing ensures that time slots are not wasted. The transmission capacity of the link is shared by only those users who have data packets to transmit.

The DTSP algorithm takes advantage of several attributes of shared networks:

1) All users are typically not connected to the network at any point of time.
2) Even when connected, the users do not transmit data (or voice or video) all the time.
3) Most traffic in a packet radio network is "bursty". Hence, there are gaps between packets of information that can be filled with other users' traffic.

It should be noted that multihop design for TDD-OFDM cellular networks is still under investigation. Therefore, there are no generally used standards or specifications in the literature. Hence, for our OFDM-based two-hop architecture, we consider the specifications of UTRA-TDD network which indicates a time frame of 10 ms with 15 time slots per frame [42]. The BS considers the MSs in the inner region and the GTWs at the boundary of the inner and outer regions to be a single group of entity. The MSs in the clustered outer-layer constitute the second group. The MSs in the clusters are selected for transmitting data in a round-robin fashion according to their ID number.

4.2 Time Slot Allocation in DTSP

Fig. 6 presents the frame structure and the time slot allocation according to the DTSP algorithm. The uplink and downlink time frames are independent of each other. In case of uplink time frame, all time slots except the first time slot carry data signals. The first one is divided into two equal parts: *control section* and *data section*. The control section is further divided into two equal parts: *uplink control section* and *downlink control section*, as shown in Fig. 6.

There are $N/4$ mini slots each for uplink and downlink control section. The $N/4$ mini slots in the uplink control section are used by different wireless devices to send control signals to the GTW node. The next $N/4$ mini slots in the uplink frame are for downlink control section, wherein, the GTW broadcasts information to the MSs. Thus, only $N/4$ devices can be controlled over any frame, and hence, a maximum of $N/4$ MSs per cluster can be served at any time frame. The shaded box in Fig. 6-b, indicates the difference between the uplink and downlink time frame. In the downlink frame, there is no control section, as shown in Fig. 6-d. This is because, in case of downlink:

1) There is only one transmitter and many receivers, unlike the case of uplink where there are several transmitters and one receiver.

Parameter	Description of Parameter
F	Number of time frames in a superframe.
S	Number of time slots per frame.
N	Maximum number of minislots per time slot.
GTW′ and GTW″	Diametrically opposite gateways in a cell.
n	Number of MSs under GTW′.
b_{U_n}	Buffer size of mobile node, n, for transmitting to GTW′.
$b_{U_{\mathrm{GTW''}}}$	Buffer size of GTW″ for transmitting to BS.
γ_{D_n}	C/I ratio of GTW′ → MS_n in previous frame.
$\gamma_{D_{\mathrm{GTW''}}}$	C/I ratio of BS → GTW″ in previous frame.
γ_{U_n}	γ ratio of MS_n → GTW′ in current frame.
$\gamma_{U_{\mathrm{GTW''}}}$	γ ratio of GTW″ → BS in current frame.
ζ_{U_n}	Modulation scheme of data packet from MS_n → GTW′.
$\zeta_{U_{\mathrm{GTW''}}}$	Modulation scheme of data packet from GTW″ → BS.
$t_{U_{\mathrm{GTW''}}}$	Time required by GTW″ to transmit packets to BS.
t_{U_n}	Time required by MS_n to transmit packets to GTW′.
$\zeta_{D_{\mathrm{GTW''}}}$	Modulation scheme of data packet from BS → GTW″.
$\zeta_{D_{\mathrm{MS_p}}}$	Modulation scheme of data packet from GTW′ → MS_p.
t_{D_n}	Time required by GTW′ to transmit packets to MS_n.
$t_{D_{\mathrm{GTW''}}}$	Time required by BS to transmit packets to GTW″.

TABLE 1
List of Parameters and their Description

2) The transmitter (BS or GTW), knows the buffer size that is to be transmitted to the different receivers.

Table I presents the different parameters that play an important role in the DTSP algorithm. S represents the number of time slots per frame and F represents the number of frames per superframe. The most important parameters of the algorithm include: N - the maximum number of minislots per time slot, GTW′ and GTW″ - the diametrically opposite gateways in the cell, n - the number of MSs under GTW′ with the maximum value being $N/4$, b - the buffer size of the designated wireless device and ζ - the modulation scheme of the transmitted data packet, in either uplink or downlink.

4.3 Description of DTSP Algorithm

4.3.1 Control Section

As explained in the algorithm and shown in Fig. 6, a control section is reserved in the 1st time slot in the uplink frame. In the 1st minislot of the 1st part of the control section time slot, the GTW sends its buffer size to the BS. In the subsequent $\frac{N}{4}-1$ mini slots, all the MSs (maximum $\frac{N}{4}-1$ MSs) within half radius distance from the center that want to communicate send their buffer sizes to the BS. In addition, the transmitters also transmit the γ of the users of the previous downlink frame. On account of the cluster-based design, in the diametrically opposite cluster, the different MSs within the cluster communicate with their GTW at the same time instant. In each of the mini slot, the MSs in the clusters transmit their buffer sizes to the GTW and also transmit the γ between the GTW and MS (downlink) from the previous frame.

Algorithm 1 *Dynamic Time Slot Partitioning*

for $i = 1$ to F **do**
  if $i/2\ = 0$ **then**
    for $j = 1$ to S **do**
      Divide time slot j into N minislots
      if $j == 1$ **then**
        for $k = 1$ to $N/2$ **do**
          MS_k transmits b_{Uk} and γ_{Dk} to GTW′.
          GTW″ transmits $b_{U_{\mathrm{GTW''}}}$ and $\gamma_{D_{GTW}}$ to BS.
          GTW′ calculates γ_{U_k}.
          BS calculates $\gamma_{U_{\mathrm{GTW''}}}$.
          GTW′ determines ζ_{U_k} from γ_{U_k}.
          BS determines $\zeta_{U_{\mathrm{GTW''}}}$ from $\gamma_{U_{\mathrm{GTW''}}}$.
          BS determines time, $t_{U_{\mathrm{GTW''}}}$, required by GTW″.
          GTW′ determines t_{U_k} required by MS_k.
        end for
        All MSs in the cluster switch to the ′ON′ state.
        for $k = (N/2) + 1$ to N **do**
          GTW′ broadcasts ζ_{U_k} and t_{U_k}.
          BS broadcasts $\zeta_{U_{\mathrm{GTW''}}}$ and $t_{U_{\mathrm{GTW''}}}$.
        end for
      end if
      if j not equal 1 **then**
        for $p = 1$ to n **do**
          MS_p transmits data packets to GTW′.
          GTW″ transmits data packets to BS.
        end for
      end if
    end for
  else
    BS determines $\zeta_{D_{\mathrm{GTW''}}}$ from $\gamma_{U_{\mathrm{GTW''}}}$.
    GTW′ determines $\zeta_{D_{\mathrm{MS_p}}}$ from γ_{U_n}.
    BS computes time, $t_{D_{\mathrm{GTW''}}}$.
    GTW′ computes time, t_{D_n}.
    $j = 1$.
    while $j <= S$ **do**
      Divide time slot j into N minislots
      BS transmits data packets to GTW″.
      GTW′ transmits data packets to MS_p.
      Compute the increase in number of time slots, j
    end while
  end if
end for

From the received information, each GTW estimates the γ for each of the MSs in the uplink, exploiting the channel reciprocity in TDD. From the γ information and the variable amount of data from buffers, the GTW determines the different modulation technique and the required time slot duration in the uplink mode for each of the MSs. In case of downlink transmission, the GTW considers the γ of the previous frame to calculate the appropriate modulation technique and the required time slot duration. Hence, for both uplink and downlink, the information about the required time slot duration is calculated for all the users and broadcasted before the start of data transmission.

In the second part of the control section time slot (in the uplink frame), the GTW broadcasts the number of time slots allotted to the MSs for both uplink and downlink. Hence, in this part of the control section, all MSs are in 'on' state - so that all MSs can listen for the number of time slots required for all other MSs. For example, if each time slot is divided into 60 mini slots, and MS1, MS2 and MS3 are allotted 2.67, 0.5 and 1.33 time slots respectively for uplink, the MS3 knows that it has to begin its transmission after $(2.67 + 0.5 =)$ 3.17 time slots and can transmit for 1.33 time slots. Hence, every user in the network knows when it has to start its transmission and how many time slots it needs to transmit the data in its buffer. It is important to note that for the mini slots in the control section, γ is not known. Therefore, the lowest modulation order, BPSK, is used along with half rate convolutional channel coding. For an OFDM based TDD/TDMA system with N_c subcarriers, this would result in $N_c/2$ information bits. Hence, the above information is quantized and coded into $N_c/2$ bits. Fig. 6-b shows the uplink control section in detail.

4.3.2 Data Section

In case of uplink data transfer, the MSs in the outer-region transmit data to their respective GTWs. Each receiving GTW decodes the data obtained from the MSs and stores the bits in its buffer. In the next uplink frame, the GTW sends the data to the BS. At the same time, depending on the availability of time slot, the MSs located within half the cell radius from the center of cell attempt to transmit their data to the BS. It should be noted that the time frame allotment for GTW $\rightarrow$ BS is exactly the same as is during MS $\rightarrow$ GTW transmission. Given that the γ between GTW and BS could be different from that between MSs and GTW, three different scenarios could happen:

1) If γ between GTW and BS is very high, the entire buffer of the GTW is emptied within the allotted time frame. In this case, the data of the MSs in the inner-region could be transmitted in the remaining time frame.

2) If γ between GTW and BS is the same as that between MS and GTW, the entire buffer of the GTW is emptied exactly in the allotted time frame. Hence, the data of MS in the inner-region cannot be transmitted. In this case, the buffer of inner-region MS is transmitted to the BS during the time frame of the adjacent GTW.

3) If γ between GTW and BS is low, the buffer of the GTW cannot be emptied. In this case, the remaining packets in the buffer are transmitted when the next frame is allotted for data transmission from this GTW to BS.

Parameter	Value
Time frame	10ms
Time slots per frame	15
Time slot length	667 μs
BW	5 MHz
Center frequency	1.9 GHz
Number of sub-carriers	1024
OFDM symbol duration	11 μs
No. of OFDM symbols/time-slot	60
Number of mini-slots/time-slot	60
Number of cluster/cell	6
Max. No. of MSs per cluster	16
Max. No. of MSs per cell	145
No. of MSs in 7-cell network	1000

TABLE 2
System Parameters

In case of downlink transmission, there are two notable differences in comparison with the uplink data transmission. In case of downlink data transfer (GTW $\rightarrow$ MS/ BS $\rightarrow$ GTW), the GTWs or BSs send packets to all the MSs/GTW in the cluster. So, the final destination is different. Also, in the downlink, the transmitter already knows the amount of data to be transmitted to the receivers. In addition, the γ of the previous frame and the number of time slots required for the downlink are sent in the control section of the uplink frame, and therefore, known beforehand. Hence, in the downlink frame allotted for data transfer, there is no control section.

The significant benefit of the DTSP algorithm is that there is **no additional overhead or complexity** arising in case of an asymmetric traffic between the uplink and downlink. This is a very significant point, especially for data-centric communications expected in beyond 3G and 4G networks.

5 Testing and Performance Evaluation

5.1 Network Setup and Parameters

The proposed DTSP algorithm is evaluated in a cluster-based two-hop cellular network (shown in Fig. 2) and

Modulation Technique	γ Threshold	No. of bits/symbol
BPSK	4.6 dB	1
QPSK	7.1 dB	2
8PSK	11.3 dB	3
16QAM	14.2 dB	4
32QAM	17.4 dB	5

TABLE 3
γ Threshold for different modulation techniques

its performance is analyzed in terms of the time taken to transfer data packets from source to destination. A 7-cell scenario is considered in the system design, with the radius of the cell, r = 250 m and a total coverage area of 1km^2. A cluster-based network is assumed, wherein each cell is divided into a circular inner and outer region, each with a radius of $r/2$. There are 6 clusters in the outer region of a cell. 1000 uniformly distributed MSs are considered around the coverage area. This results in around 145 MSs per cell and a maximum of 16 MSs per cluster. An UTRA-TDD time frame of 10 ms is considered in the simulations. There are 15 time slots per frame. In the DTSP algorithm, the time slot is divided into 60 mini slots and in each mini slot, an OFDM symbol is transmitted. The simulation model parameters are given in Table II. A total bandwidth of 100 MHz is considered in the system design. Both uplink and downlink scenarios are considered in the simulations.

Every wireless node (BS/GTW/MS) in the cell has certain traffic to be transmitted to its destination node. The minimum data that a wireless device could transmit can be zero, and the maximum traffic/packet size at any sampling instant is restricted to 100 symbols. The time taken to transmit the packet is calculated only for the center cell whereas the traffic in the adjacent 6 cells are used mainly for calculating the interference.

It is assumed that each user utilizes up to 12 subcarriers. A slow-fading Gaussian channel with a lognormal shadowing of zero mean and a 4 dB standard deviation is assumed during the analysis. Similarly, the path-loss exponent α is considered to be 4. In addition, both simple and adaptive modulation schemes are considered in the system analysis. The adaptive modulation is set according to the γ threshold, as explained in the next subsection.

5.2 Adaptive Modulation

Under an adaptive modulation scheme, the transmitter selects the modulation technique based on two parameters: the γ experienced at the receiver and the bit error ratio (BER). For multimedia transmission in beyond 3G and 4G networks, a coded BER of 10^{-6} to 10^{-7} is required. In a corresponding uncoded network design, as in our system, a BER of 10^{-2} is however sufficient [43]. When a combination of convolutional coding and Reed

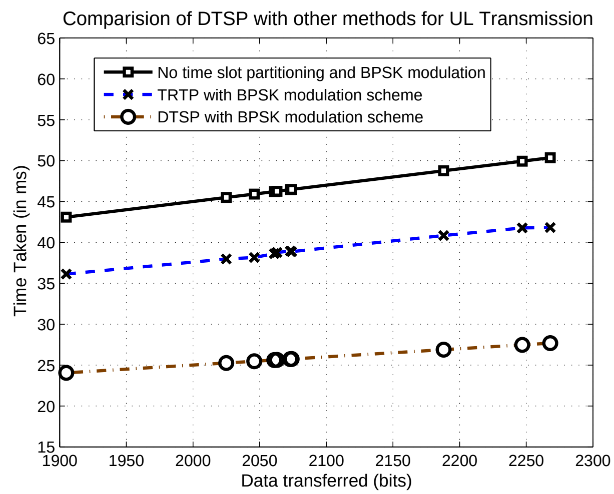

Fig. 7. Comparison of dynamic time slot partitioning (DTSP) algorithm with other time slot allocation algorithms for uplink transmission

Solomon coding techniques is considered, a BER of 10^{-2} would translate into a BER of 10^{-6} or beyond, in a coded system. For a BER of 10^{-2}, the modulation technique that could be used for a given γ is shown in Table III.

The DTSP algorithm is simulated and the network performance is analyzed for transmissions performed over two or three time frames. This is because, over a single time frame, all the wireless nodes in the network may not be able to communicate with the BS, whereas analyzing the performance over two or three frames provides a statistically averaged result. In this paper, a standard benchmarking practice is considered wherein there are multiple measurements of throughput and latency, each using a different packet size. The "average" Internet packet size is roughly 250-300 bytes or 2000-2400 bits. Hence, an observation window of 1900-2300 bits has been considered in this paper. In fact, a mix of short (64 byte, 88 byte) and medium sized packets (512 byte) were used in the actual transmission to stress the devices and network differently.

In the next section, the DTSP algorithm is compared with the OFDM based RTP algorithm [21] and a no partitioning TSA method [19], for both uplink and downlink. In addition, the downlink mode is analyzed using both a simple modulation scheme and an adaptive modulation technique. This is because, the demand in next generation wireless networks is mainly for downlink transmission.

5.3 Testing Results

Fig. 7 compares the performance of the DTSP algorithm with the time slot allocation of RTP algorithm (TRTP)

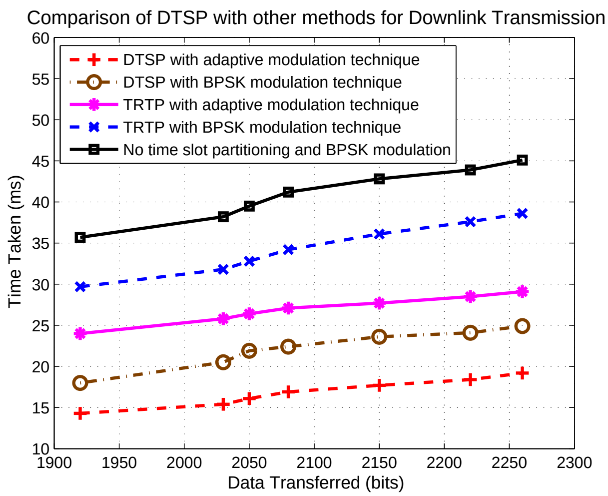

Fig. 8. Comparison of dynamic time slot partitioning (DTSP) algorithm with other time slot allocation algorithms for downlink transmission

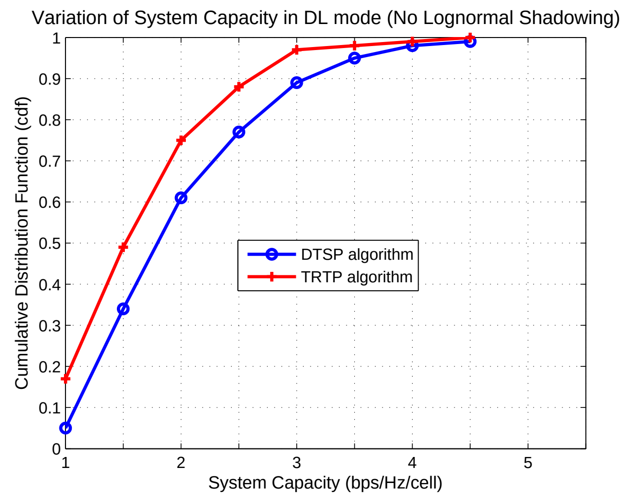

Fig. 9. Variation of System Capacity in downlink mode for DTSP and TRTP resource allocation methods with no lognormal shadowing

and with a no time slot partitioning method for uplink transmission, when a simple BPSK modulation technique is used. The DTSP, TRTP and no time slot algorithms are compared in terms of two parameters: the time taken to transmit certain number of bits, and secondly, the achievable system capacity. Following the requirements of next generation wireless systems, the focus of this paper is on downlink transmission. Hence, most of the results are for downlink mode. However, the DTSP algorithm also scores better than the other methods in uplink mode.

It can be observed that the time taken for all the MSs in the cell to transmit their packets to the BS is the least in case of DTSP algorithm. For example, the time taken for TRTP algorithm to transmit 2000 bits is 38 ms, whereas, in case of DTSP, it is 25 ms. Hence, DTSP gives nearly a 33% reduction in the time delay as compared to the TRTP method. Significantly, this margin is maintained even with an increase in the number of total bits to be transmitted in the cell.

In a similar test, Fig. 8 compares the performance for downlink transmission. The time required for TRTP algorithm to transfer 2000 bits is 32 ms while for DTSP algorithm, it is 20 ms, again a reduction of 37%. In contrast, a non time slot partitioning algorithm requires 38 ms, nearly double the time required by DTSP algorithm. Fig. 8 also shows the results obtained when an adaptive modulation technique is used. It can be seen that in the presence of adaptive modulation, the time required by DTSP reduces notably, as compared to the BPSK modulation technique. The main reason why DTSP scores better than RTP and the non-partitioning time slot allocation algorithms is that DTSP is based on

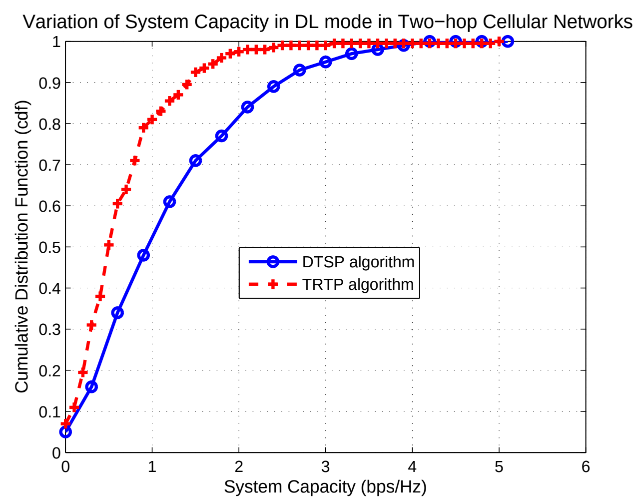

Fig. 10. Variation of System Capacity in downlink mode for DTSP and TRTP resource allocation methods with lognormal shadowing

asynchronous TDM, and hence, the different users can transmit their different-sized packets without any loss of the radio resources.

The system capacity of DTSP and TRTP algorithm is compared for downlink mode, both in the presence and absence of lognormal shadowing. Fig. 9 shows the achievable system capacity in downlink mode when there is no lognormal shadowing. It can be observed that the expected value of the system capacity for DTSP algorithm is 1.82 bps/Hz/cell, whereas that obtained by the TRTP algorithm is 1.46 bps/Hz/cell, 19.78% less than that of DTSP algorithm. In the presence of lognormal shadowing, the expected value of the system capacity reduces considerably. Fig. 10 shows the results for downlink mode in the presence of lognormal shadowing. The expected value of the DTSP algorithm in the presence of lognormal shadowing is 0.95 bps/Hz/cell, whereas that obtained from the TRTP algorithm is 0.56 bps/Hz/cell, a 41% reduction from the DTSP algorithm. In addition, by comparing Fig. 9 and Fig. 10, it can be observed that the expected value of DTSP algorithm reduces from 1.82 bps/Hz/cell to 0.95 bps/Hz/cell in the presence of lognormal shodowing, a drop of 45%. In contrast, in the presence of lognormal shadowing, the expected value of the TRTP algorithm reduces from 1.46 bps/Hz/cell to 0.56 bps/Hz/cell, a reduction of 61%, significantly higher than that of DTSP algorithm. Hence, both in the presence and absence of lognormal shadowing, the DTSP algorithm performs significantly better than the TRTP algorithm.

5.4 Benefits and Deployment Issues

The tests show a significant improvement in capacity and reduction in delay when employing the proposed DTSP algorithm. However, there is a cost of employing DTSP, mainly in the form of an increase in the complexity at the relay nodes, as they would receive from or transmit to the BS, and then re-transmit to or receive from the mobile nodes. Importantly, in the cluster-based design, the relay nodes are either fixed relays with greater computation power or high-end wireless relay nodes like laptops, PDAs, etc. that can perform the extra computations without any difficulty.

In terms of overhead, the DTSP necessitates an additional control section period of $N/4$ where N is the number of mini slots per time slot. However, the benefit gained from the dynamic partitioning of time slots in terms of the increase in the overall throughput is significantly greater than that lost by the additional overhead as can be seen in the results. For instance, the control signal information is only over one half the time slot for every frame. Even when the lowest (BPSK) modulation scheme is considered, the control information takes 30 symbol periods in comparison with $60 \times 16 = 960$ periods of a complete frame. The additional overhead of only 3.1% is well worth the DTSP throughput improvement of around 33% as illustrated in Fig. 7 and Fig. 8. Hence, the increase in the overhead can be considered negligible in comparison with the benefit.

A significant flexibility of DTSP is that the nodes with their own traffic can arrive in the cluster and depart from the cluster at any time. Another aspect that makes DTSP quite practical to implement in the cluster-based two-hop design is that there is no predefined dedicated assignment of time slots to the nodes. However, at the same time, it should be noted that the functioning of DTSP requires hierarchical network architecture, where there is one transmitter transmitting to all nodes in its coverage area or many nodes transmitting to one receiver.

An additional challenge of deploying the proposed scheme is the cluster management. This includes cluster-head selection in order to maintain both the efficiency of the hierarchical architecture and the fairness of the relay-node distribution. A simple-to-deploy algorithm would imply having fixed nodes as relays. A more complex solution would be to have mobile relays. The management of mobile relay nodes for multihop communications is still an open research area. A related issue is the node allocation to the clusters. This can be easily performed based on the distance or/and path-loss between the node and the cluster-head relay node. Importantly, both these issues are architecture-related issues and are not directly related to the proposed DTSP algorithm. A third issue is the effect of having imperfect synchronization between the simultaneously communicating pairs of nodes in the cluster-based design, and separate solutions need to be considered to minimize their effect.

6 Conclusion

A novel *dynamic time slot partitioning (DTSP)* algorithm based on *statistical multiplexing* is proposed for time slot allocation in two-hop cellular networks, for an OFDM based TDD/TDMA air interface. The DTSP algorithm proposes that each slot be partitioned into several mini slots. These minislots are dynamically assigned to different number of users, depending on the amount of data each wireless device in the network has to transmit or receive. The main advantage of DTSP algorithm is that there are no cross-time-slot regions, as there is no random simultaneous transmission of packets by different users in the same mini slot. Only the pairs that are located diametrically opposite to each other communicate simultaneously. In addition, the statistical multiplexing ensures that data packets are transmitted sequentially without any loss in the time slot resource. This results in a much higher system capacity as compared to other time slot allocation algorithms. Significantly, the DTSP algorithm works well for any kind of traffic asymmetry ratio between uplink and downlink mode in the cellular network. This is especially beneficial for multimedia streaming and video transmission in the downlink direction, the essential requirement for next generation wireless systems.

Acknowledgment

The author would like to thank Dr. Sinan Sinanovic, Prof. Harald Haas from the University of Edinburgh, UK and Prof. Juergen Schoenwaelder from Jacobs University Bremen, Germany for their advise and critical comments during the initial part of the research work. Importantly, the authors would like to thank Irish Research Council for Science Engineering and Technology (IRCSET) for their graceful support.

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