Improving Wireless TDMA/FDD MAC Performance with Multi-beam Directional Antennas

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Abstract—**In this work presented, the effects of the multi-beam directional antennas on the performance of a new wireless TDMA/FDD system have been studied. Directional antennas (DA) inherently have the ability to enable development of the SDMA systems, and to allow transmitting and receiving signals simultaneously at the same time slot. Employing a dynamic slot allocation table at the base station with 4 or 8 sector directional antennas and holding the wireless terminals location information, a new SDMA/TDMA/FDD frame structure has been developed for wireless communications. The preliminary simulation results obtained using OPNET Modeler show that the proposed SDMA/TDMA/FDD system has substantially increased the traditional TDMA/FDD system capacity and provides 1.37 to 4 times better mean delay results when the number of users is increased from 4 to 32 under the same load in the wireless network models.**

Index Terms—**SDMA/TDMA, Directional Antennas, MAC**

I. Introduction

Together with the developments in high performance wireless computers and other mobile devices, the importance of wireless/mobile data communication has been increased, and the use of directional antennas has gained more importance to enhance the network capacity. Recently, there has been a remarkable interest in developing MAC protocols for wireless networks which are equipped with directional antennas.

Smart antennas generally known as directional antennas are one of the most promising technologies that enable a higher capacity in wireless networks by effectively reducing multi-path and co-channel interference and allowing multi-sector implementations. This is achieved by focusing the radiation pattern only in the desired direction. Smart antennas employ a set of radiating elements arranged in the form of an array. The signals from these elements are combined to form a steerable or switchable beam pattern that follows the desired user or a group of users. In a smart antenna system the arrays by themselves are not smart; it is the digital signal processing that makes them smart. The process of combining the signals and the focusing the radiation pattern in particular direction is often referred to as digital beamforming [1 and 2].

In this work presented, a new MAC model based on SDMA/TDMA/FDD (Space Division Multiple Access / Time Division Multiple Access / Frequency Division Duplexing) using directional antennas has been designed, simulated and compared to a regular TDMA/FDD MAC counterpart employing omni-directional antennas. The performance metrics used for performance analyses are end-to-end delay and throughput. In the proposed MAC model, WTs (Wireless Terminals) use omni-directional antennas and communicate through a BS (Base Station) which is equipped with multi-beam directional antennas containing beamforming modules for both receiving and transmitting, each of which is capable of directing a beam at an intended sector in the space. The system model uses FDD for dublexing technique and employs a DSAT (Dynamic Slot Allocation Table) at the BS that is especially utilized for determining to which WT the slot will be assigned in the uplink (WT to BS) direction. By means of the DSAT at the BS, an SDMA/TDMA/FDD frame structure is constructed. This approach ensures an increased wireless system capacity, meanwhile reducing end-to-end delays.

The paper is organized as follows. Section 2 begins with a brief explanation of directional antenna systems, multi-beam directional antennas and antenna models used. Section 3 provides an overview of the TDMA/FDD MAC protocols utilizing directional antennas, which is used for performance comparisons. Overall properties and design stages of the proposed SDMA/TDMA/FDD MAC protocol together with related algorithms are explained in detail in Section 4. Section 5 includes an example network scenario employing the proposed MAC technique, which has been modeled and simulated under different traffic loads and varying number of users, with OPNET Modeler including the Radio Module. The simulation results obtained are compared with those of another TDMA/FDD MAC based model utilizing omni-directional antennas under the same network conditions as proposed model. And, the last section gives our summary with final remarks.

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II. Directional Antennas Overview

Recently, the need for providing high quality wireless access and the great demand on high speed wireless links have increased dramatically. Consequently researchers have been motivated to enhance the wireless network capacity to meet the growing subscriber and different application requirements. As a result, new sources have been focused on increasing the overall network performance. The use of directional antennas, especially designed to achieve the throughput expansions and to reduce the communication delays, is of much importance [2, 3, 4, 5 and 6].

There are several techniques of implementing directional antennas. Basically, they are described in two categories: switched beam systems and adaptive array systems [2]. The switched beam antenna system has a switching mechanism enabling it to select and then to switch the right beam which gives the best directivity and gain to the terminal under consideration. This technique does not steer or scan the beam in the direction of the desired signal. Switched beam systems can be divided into two groups: single beam and multi-beam directional antennas. In single beam directional antennas, only one beam is active at a given time. Simultaneous transmissions are not allowed because in this system there is only one transceiver. On the other hand, in multi-beam directional antennas, there are several beam patterns and each beam is directed to a different user or a sector. Therefore, simultaneous transmissions are allowed at the same time and frequency. As a result SDMA is achieved as utilized in this research study. Here, the number of beams is equal to the number of transceivers.

The adaptive array system tracks the mobile user continuously by steering the main beam towards the user and at the same time forming nulls in the directions of the interfering signal. This antenna system is out of the scope of the works carried out and presented here, and therefore is not explained in detail.

III. Wireless MACs with DAs

In the last few years, directional antennas have been extensively considered for use in both wireless centralized and ad-hoc network architectures. High costs and complexity of the WTs with directional antenna systems lead to difficulties in implementation of ad-hoc network architectures. On the other hand, a centralized architecture, where a base station has directional antennas while the WTs are equipped with omni-directional antennas, is considered more suitable and reasonable than the ac-hoc network architecture. Considering this point, the study presented exploits the wireless centralized architecture with the idea of further development including quality of service support for real-time multimedia applications [6 and 7].

In [8], multiple beam adaptive arrays (MBAA) were used to improve the performance of a slotted ALOHA packet radio network. When used in a packet radio system, an MBAA can successfully receive two or more packets simultaneously. Each beam captures a different packet by automatically pointing its pattern toward one packet while nulling other contending packets. As a result, the capacity of the system can be increased compared with the conventional ALOHA due to a remarkable reduction in the effect of collisions. Differing mainly from this work, our proposed approach using SDMA/TDMA/FDD overcomes collisions resulting in high system performance.

In [9], a MAC protocol was proposed to achieve throughput multiplication of wireless LANs, employing a slot reservation mechanism combined with SDMA. The most important benefit of this protocol is that it can adaptively adjust its partition time-space slots based on the network traffic to optimize the throughput and delay performance. As designed for mobile terminals, it exploits an adaptive array antenna with a complex and expensive signal processing unit in the BS. It differs from our simple and easy approach to implement system with sector antennas in that the latter is much more appropriate and cost-effective for stationary wireless terminals considering most of their applications, which are hardly mobile in time, require only fixed-wireless services, also providing foundations for quality of service supported real-time multimedia applications.

The performance of slotted ALOHA when the BS receiver uses multi-beam directional antennas capable of steering the beams selectively on smaller sectors was analyzed in [10]. Under high load conditions, steered beams with long beam service times offer better performance, whereas under light load conditions, static coverage patterns are better. The use of multi-beam directional antennas in the BS to realize sectors in this research work is partially benefited in our proposed MAC protocol.

A TDD-SDMA/TDMA system with a multi-slot assignment for downlink in packet-switched wireless network was presented in [11]. It could assign more than one time slots for downlink to each terminal so as to deal with the asymmetric traffic in packet-switched services. In the proposed system, an efficient algorithm was reported to decide the priority of time slots for downlink, by which the maximum of potential transmission rate for downlink could be obtained.

IV. Proposed TDMA/FDD MAC with DAs

In our proposed MAC protocol, utilizing the TDMA/FDD MAC approach presented in [12], TDMA is preferred as a multiplexing technique due to its simplicity, easy implementation and appropriateness for further development for real-time multimedia applications requiring quality of service support [9 and 13]. By virtue of TDMA, radio spectrum is divided into time slots that can be assigned to different connections where a user can send data only in its own dedicated time-slot. Due to the FDD duplexing technique utilized in the proposed TDMA MAC protocol, two distinct carrier frequencies are used for the uplink and downlink channels. For the system under consideration, the BS is equipped with an N-element antenna array for uplink and downlink communications. In this way, the space has been divided into N sectors, thus SDMA has been exploited. There are also M wireless terminals which are equipped with omni-directional antennas [13].

Wireless terminals are not able to communicate directly one another in the proposed method as opposed to the Ad-Hoc networks. They communicate through a centralized base station. When a WT needs to communicate with any other terminal, initially it asks for a transmission time slot from the BS (using the CT slots shown in Fig. 1). Having its time-slot reserved (using the CB slots), the WT starts transferring data.

Data packets generated in the wireless terminal are first destined to the BS. The BS is responsible for queuing these incoming packets and arranging their transmission, using its DSAT algorithms, to the destination WTs in the reserved time slot.

If there is not any slot available for the request, a connection can not be established and the WT may later attempt to connect again sending another connection request to the BS. The slotted frame structure of the proposed MAC protocol is shown in Fig. 1.

The proposed MAC protocol is divided into two main complementary parts operating at the WT with an omni-directional antenna and BS with directional antennas. Data transmissions can be provided when these two MAC parts work synchronized. The following sub-sections explain in detail all functions and algorithms in both parts together with their translation into the modeling and simulation environment in the OPNET Modeler.

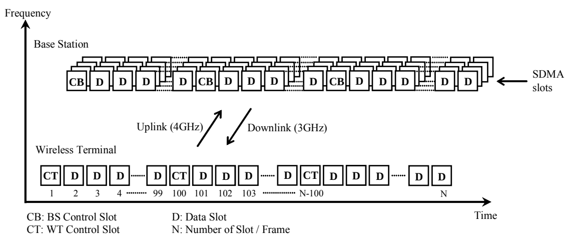

Fig. 1. SDMA/TDMA/FDD frame structure of the proposed MAC protocol.

The proposed MAC protocol includes three main processes to implement the WT functions and algorithms. The first is to request a connection establishment / termination from the BS, the second is to obtain its own time slot from the BS utilizing the DSAT and the last is to send data in the allocated time slot.

Before sending/receiving data to/from other terminals, a terminal must first inform the BS about its time slot requirement. In this regard, it creates a control packet called *con_req_packet* (Fig. 2.a) containing its own terminal address and sector number indicating which beam needs to be activated by the BS to communicate with this terminal. Then this packet is sent to the BS in the first available uplink control slot (CT). After a connection is established, the BS knows the WT's sector information recorded into the SectorNo field in the DSAT (Figs. 2 and 5), and the WT is acknowledged about its assigned time-slot to transfer data (Fig. 2.c). The WT creates a control packet called *con_end_packet* to terminate the connection and sends it to the BS in the first available uplink CT again (Fig. 2.d). After that, the BS releases this data slot (D) for use by other WTs.

a)

TermAddress (8 bits)	SectorNo (8 bits)	CRC (16 bits)

b)

TermAddress (8 bits)	TimeSlot (8 bits)	SectorNo (8 bits)	CRC (16 bits)

c)

TermAddress (8 bits)	DestAddress (8 bits)	SectorNo (8 bits)	CRC (16 bits)
PAYLOAD (984 bits)			

d)

TermAddress (8 bits)	TimeSlot (8 bits)	SectorNo (8 bits)	CRC (16 bits)

Fig. 2. a) Connection request packet (con_req_packet),
b) Connection response packet (con_res_packet),
c) SDMA/TDMA data packet (data_packet),
d) Connection terminate packet (con_end_packet).

The WT node model designed using OPNET Modeler is shown in Fig. 3.a. The SOURCE module used in the WT is responsible for packet generation according to the packet size and arrival time parameters defined. The SINK module collects statistics of the arrived packets and then destroys them.

The MAC module manages the allocation of existing bandwidth shared by all WTs. The physical layer components used in the model are rx, rx_ant, tx and tx_ant. They provide the interface between the node module and air (Fig. 3.a).

In Fig. 3.b, the process model of the MAC module used in WT node model is illustrated. The con_req state machine creates connection request packets and sends them to the BS. Using the from_src state machine, data packets received from the SOURCE are sent to destination (through the send state machine) in the connection time slot allocated. The req_resp state machine obtains the connection time slot that is assigned by the BS using its DSAT scheduling algorithm. The con_end state machine creates the connection termination packet and sends it to the BS. The from_rx state machine delivers any arrived packets destined to this WT through its MAC layer.

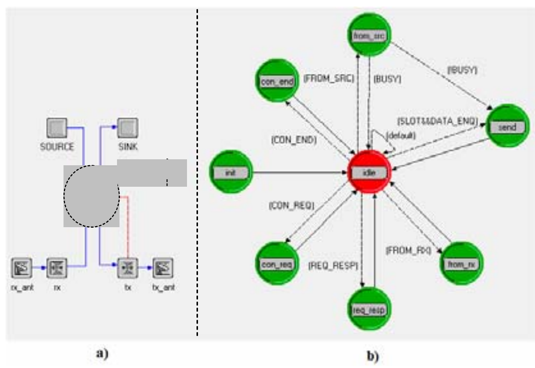

Fig. 3. a) The WT node model, b) The WT MAC module process model.

The BS node model of the proposed MAC protocol includes

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three main modules. These are namely the Antenna Controller, the Antenna Pointer and the BS MAC. The Antenna Controller module gets packets from its antennas each directed to a different sector in the space and transfers them to the BS MAC module. It also gets packets from the BS MAC module, and having extracted SectorNo information, it transmits the packets to the related sector. Antenna Controller module has also capabilities getting and sending multiple packets simultaneously.

Antenna Pointer module has predefined individual beams and each beam covers a specified sector in the space. These beams are assumed to have almost ideal shape for receiving and transmitting in the desired direction and rejection in the other directions. For transmission, this module points its main beams to the desired directions in the space. In the antenna module, 4 beams and 8 beams are used. When used a 4-beam antenna, each of these 4 beams is directed to a different sector: North-East, North-West, South-East and South-West. For reception, antenna controller module monitors the signal levels on all beams after that the packets having the signal with the power over the predefined threshold level are forwarded to the BS MAC, while the others are discarded as interference.

The BS MAC includes three main processes. These are namely, assigning a time slot for a connection using its DSAT scheduling algorithm, forwarding any arrived data packets to their destinations and terminating any active connection. The most important and primary function of the proposed MAC protocol is the efficient management of the DSAT.

Fig. 4.a shows the BS node model realized using OPNET Modeler. The MAC module functions in the BS node are used to allocate available time slots to the WTs requesting connection and to downlink actual data packets to the intended WTs.

The MAC module process model designed is given in Fig. 4.b. The from_rx state machine delivers arriving packets to the next state machine according to the packet formats. The con_req state machine executes the scheduling algorithm managing the DSAT. The data state machine delivers data packets and finally the con_end state machine handles connection termination requests.

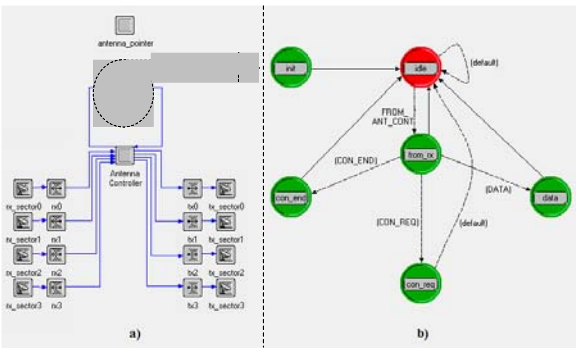

Fig. 4. a) BS node model, b) BS MAC module process model.

The DSAT and its scheduling algorithm running in the BS are the most vital parts of the proposed MAC protocol. The structure of DSAT is shown in Fig. 5.

For a new connection request, a WT sends a con_req_packet to the BS. After that the BS looks up its DSAT table whether there is any available time slot to be allocated. If so, the BS assigns a time slot to the WT using the WTs position information (SectorNo) contained in the con_req_packet and updates the DSAT accordingly. Then BS creates con_res_packet and sends it to the destination WT. A connection may not be established if there is not any available empty time slot. The WT repeats this connection request procedure until it succeeds.

For a connection termination request, the BS gets con_end packet from the WT and extracts the time slot number from it. It then releases this time slot for a new connection, updating the DSAT. Finally, a con_end_packet is created and sent to the related WT.

For a data packet, the BS extracts the sector number information from the 'SectorNo' field and determines in which sector the related WT is located. After that the beam used for this sector is activated to transfer data.

Certain number of slots (i.e. 1, 100, 200, ..., N-100) in the DSAT called control slots (CT) are reserved for connection request and connection termination packets. When a WT wants to send a control packet for connection request or termination, it uses the first empty control slot.

Number of Sectors \ Time slots	1	2	3	4	5	6	7	9	10	....	N
1	1	4	14	16	NU	NU	NU	NU	NU	....	CB
2	2	3	13	15	NU	NU	NU	NU	NU	....	CB
3	5	7	9	11	NU	NU	NU	NU	NU	....	CB
M	6	8	10	12	NU	NU	NU	NU	NU	....	CB

NU : None Used Slot, CB : Base Station Control Slot.
M : Number of Sectors, N: Number of Time Slots.

Fig. 5. Structure of the Dynamic Slot Allocation Table (DSAT).

In this study, we consider WTs operating in omni-directional mode and the BS in directional mode. The BS has a switched-beam directional antenna comprised of multiple beam antenna arrays for both reception and transmission. Each antenna array with M elements forms non-overlapping sectors covering an angle of 360/M degrees so as to collectively cover the entire space as shown in Fig. 6. The beam shape is assumed as conical. Since the exact antenna structure is out of this work's scope, the impact of side-lobe interferences is considered insignificant. In the computer model developed, OPNET Antenna Pattern Editor is used to model the antenna pattern. In this editor, the main beam and side beam coverage range are set by the transmitting power and the antenna gain. Given a gain value gm, the antenna pattern for this gain consists of main beam of bandwidth θm, and a side beam of gain gs of bandwidth (2π- θm). We have used two different antenna patterns. The first one has 4 beams, conical shape of beamwidth $2\pi/4$ radians and gain of 10 dBi for main beam and -20 dBi for the others. The other has 8 beams, conical shape of beamwidth $2\pi/8$ radians and gain of 10 dBi for main beam and -20 dBi for the others.

V. Computer Simulation of the Proposed MAC with DAs

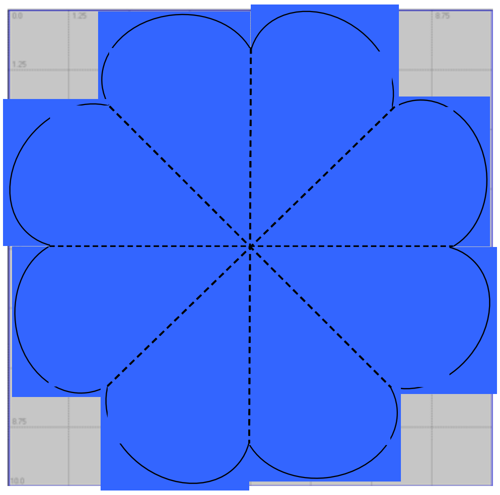

Fig. 7. The simulation scenario of the proposed MAC with 8-Beam directional antennas.

The stationary (fixed wireless) WTs and the BS in the example scenario implemented using OPNET Modeler (Fig. 7), employ the proposed SDMA/TDMA/FDD based MAC protocol, which has been explained in the previous section, to communicate with each other in the same wireless environment. Diameter of the cell which constructs the network topology is chosen 10 kilometers. The simulation models consider firstly the TDMA/FDD with 4-Beam directional antennas, secondly TDMA/FDD with 8-Beam directional antennas, and finally TDMA/FDD with an omni-directional antenna (where spatial reuse is not exploited) for consistent performance comparisons, under the same networking conditions. The simulation environment is divided into 4 equal sectors for 4-Beam and 8 equal sectors for 8-Beam directional antenna models. Each BS antenna is directed towards one of these sectors. The sectors contain equal number of WTs to be able to compare the simulation results fairly.

In the example models shown in Fig. 7, for the TDMA/FDD with 8 beam directional antennas, there are 24 WTs on which data are generated, transferred and received. The data traffic introduced to the network by any WT is randomly destined to another WT. The simulations are repeated for both different number of users and increasing offered loads.

Simulation results of both a TDMA/FDD model and SDMA/TDMA/FDD models with 4 sectors and 8 sectors described above are presented under varying network load conditions followed by performance comparisons and analysis. In the simulation environment a free space channel propagation model. To avoid the transient effects, the simulation statistics are flushed after approximately 10 seconds. For the simulation models, a slot length of 200 μseconds which has been determined considering 25 Mb/s data rate has been chosen. The simulation parameters used are given in Table 1.

Table 1: Simulation parameters

Uplink/Downlink Data Rate	25 Mbps
*Data Packet Size**	1024 Bits
TDMA frame length	200 μsn
Frequency Band	Uplink = 3 GHz and Downlink = 4 GHz
Transmitter Power	BS = 10^{-2} W and WTs = 10^{-2} W
Modulation Schema	QPSK
Directional Gain	10 dBi (main beam) and -20 dBi (side beam)
Packet Reception Power Threshold	1.2×10^{-12} W
Simulation Time	1 Hour
**Generated using Exponential Distribution Function Exp(Mean).*	

The performance metrics concerned in this research work are average end to end delay (EED), normalized average end to end delay and throughput.

Fig. 8 shows the average EED results for the proposed MAC models with 4 and 8 sectors, normalized with those of the standard TDMA/FDD MAC based counterpart as a function of the increasing number of users. As seen from the figure, the proposed TDMA/FDD model with 4 sectors and 8 sectors with different number of users outperform the regular TDMA/FDD model. The simulation models employing the TDMA/FDD with 4 sectors and 8 sectors provide up to 4 times and 6 times better average EED results, respectively. In addition, the more the number of users, the more improved results the proposed approach presents.

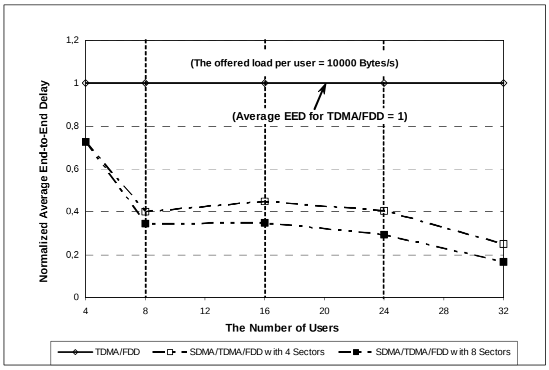

Fig. 8. Normalized EED results for the MAC models

In Fig. 9, the system throughput results for the proposed and regular TDMA/FDD MAC models are presented. As the number of users is increased, for the TDMA/FDD MAC with 4 sectors and 8 sectors, the system throughput rises linearly while saturates for that of the classical approach when the number of users is over 16. Referring to the Fig. 9, these results also clarify the reasons both for the increasing average EEDs for the classical TDMA/FDD MAC model with above 16 users and for better average EEDs for the models using the proposed approach.

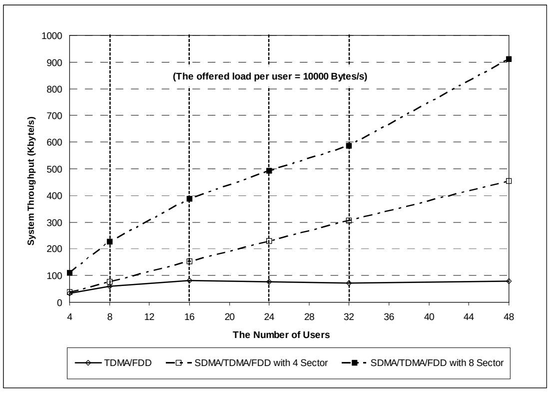

Fig. 9. System throughput for the proposed and regular TDMA/FDD MAC models.

VI. CONCLUSIONS

This paper introduces an SDMA/TDMA/FDD based MAC protocol proposal for wireless data communications. Its design stages and employment in different wireless networking systems with 4 and 8 sectors are outlined, and a detailed performance analysis compared with a regular TDMA/FDD based MAC counterpart is presented.

The simulation results obtained conclude that especially system capacity, average EED and system throughput of the proposed SDMA/TDMA/FDD based MAC models are much better than those of the regular TDMA/FDD based MAC model, as a consequence of new algorithms introduced in the BS. The simulation models employing the proposed TDMA/FDD MAC with 4 sectors and 8 sectors improve the average EED results up to 4 times and 6 times, respectively. As the number of users is increased, for the TDMA/FDD MAC with 4 sectors and 8 sectors, the system throughput rises linearly while saturates for that of the classical approach when the number of users is over 16. The comparative simulation studies realized verify that the use of proposed SDMA/TDMA/FDD approach substantially increases the traditional TDMA/FDD system capacity, which is one of the most crucial issues in wireless networking environments.

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