WiMAX Fast-moving Access Network

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Abstract—Facing the challenge of providing broadband access to high speed vehicle on motorway scenario, this paper discloses a fibre network employing star-tree architecture with a central control system in the middle to connect fixed line data collection part on one side and the wireless points to transmit information needed to on road vehicles on the other side. To implement the system, an effective coverage scheme is presented by using radio-over-fibre (RoF) technologies, in which time slot distributor (TSD) plays a key role in avoiding co-channel interference. With adaptive modulation approaches under different channel condition, a buffer management scheme (BMS) could achieve a better system performance. Furthermore, within new frame structure, four handover indicators are added to deal with the fast handovers involved among remote antenna units (RAUs) governed by single base station (BS) and handover between different BSs.

I. INTRODUCTION

The Internet is currently undergoing its most significant changes in history from wired networks to wireless networks. People were made used to an unlimited information exchange around the world. Now they want to take these opportunities out of their homes and offices. Therefore the Internet has to get mobile. This change has introduced new challenges to network and protocol designers. The preferences and requirements of wireless communication are significantly different from wired networks. As wireless links are subject to link losses, high jitter in throughput or delay and frequent handovers, the network has to react much more on alterations in connection performance as used from cabled ones. Modern mobile radio communication will bring wireless broadband access to all users. But due to several reasons, like ubiquity, mobility, or bandwidth, no current system will be capable of supporting mobile communication as it is expected by customers and vendors. For example, providing broadband access to high speed vehicle on motorway scenario at expected data rate is still a big challenge. Key issues among them are how to deal with the effect of Doppler Shift; how to enable a better use of infrastructure and make the system design to be cost-effective; how to model the channel correlation and select a suitable cell size.

Research carried out within our project is targeted towards transforming our wireless techniques so that they can operate on (i) fast moving vehicles with high impairments encountered at high data rates (ii) small cellular cells which are key to high data rate operation and (iii) more frequent cell hand-overs dictated by speed and small cell size. Furthermore, research directed at detailed statistical analysis of data from inductive loops is carried out for traffic monitoring, prediction, grooming and control [1].

Many researches have been carried out for road vehicle communication systems, in which most of them adopt millimetre-wave (mm-wave) bands in order to supply a high-speed user with high data rate traffic [2]. This leads to set up a new system without a unique standard to follow. Here we tend to apply World Interoperability for Microwave Access (WiMAX) in a motorway scenario [3], so as to combine both advantages of mm-wave for high data rate and microwave for standardisation.

This paper proposes a system structure of motorway access network based on the existing motorway infrastructure: wireless access points are mounted at the top of road side masts while optical fibres buried along the motorway construct the backbone of the network linking to a central control system. In section III, we mainly analyses how to increase the effective coverage of wireless signal on motorway scenario. By dividing conventional size of BS into a certain number of picocells, the effective coverage of motorway-picocells could be figured out based on the width of motorway and the length of overlap. This radio fibre network architecture is implemented in section IV, followed by cross layer design [4, 5], especially the progress we have made on wireless system medium access control (MAC) protocols design for a motorway scenario. Four handover indicators are introduced to deal with the frequent handovers involved among remote antenna units (RAUs) governed by single base station (BS) and handover between different BSs.

II. SYSTEM STRUCTURE OF MOTORWAY ACCESS NETWORK

To enable a better use of motorway infrastructure, here we propose an access network architecture for packet-based delivery of media-rich services as shown in Fig. 1. The fibre network employs star-tree architecture with a central control system in the middle to connect fixed line data collection part on one side and the wireless points to transmit information needed to on road vehicles on the other side. It uses Dense Wavelength Division Multiplexing (DWDM) to transmit over a single mode fibre (SMF) to several base stations (BSs) allowing expanding the capacity of the network and with an effectively cost. Using Optical Add-Drop Modules (OADMs) by fibre blown splitters to BSs located along the highway will allow us the use a SMF for several BSs, reducing the amount of existing dark fibres on highways. Erbium-Doped Fibre Amplifiers (EDFAs) would compensate for fibre losses due to long runs.

Inductive loops buried along the highway transmit traffic data through SMF to Traffic Wales central database. These historical and
real time data are then analysis based on traffic statistic model. Central control system will deliver the results to terminal users through different control station (CS) and BS according to different demand. At the same time, the wireless vehicular terminal users on highway can also access to the Internet and on road digital cameras through gateway or image processing controlled by central control system. A high performance unlicensed 5.470-5.725 GHz WiMax band directly modulated over a bi-directional SMF link is proposed and the system is intended to support about 100 Mbit/s.

III. WI-FAN SYSTEM DESIGN AND IMPLEMENTATION

Based on the effective coverage scheme, this session mainly discusses the system implementation by using radio-over-fibre technologies. When converting conventional BS into motorway picocells, the question raised by this converting process is the overlap areas between different picocells and how to deal with many increased handovers and co-channel interference evolved [6, 7]. One ideal situation would be to increase the effective areas of the coverage, but keep the handover process between different picocells as simple as possible without putting unnecessary burden on mobile stations and can avoid the co-channel interference. To achieve the above object, we disclose a novel approach of system implementation which can solve all the problems properly (see Fig. 2).

![System structure of converting classic cell to motor-picocells](image)

In this architecture, control station (CS) works as a central control system responsible for exchanging information among different BSs, while each BS is connected with a RoF subsystem [8, 9]. The buffer in CS works as an intelligent caching based on the grouping of BSs. All WLAN access points of one specific region, namely a longer section of a motorway, are combined to one cluster and connected to a network node with caching functionality. There are no specific requirements made on these links and legacy network connections can be employed for it. The caching node itself is attached to the Internet so that the access to services and data is guaranteed [10].

In RoF subsystem, the BS, which is located at the central station, connects with a headend unit including modulation and demodulation modules. The headend unit in turn connects with a certain number of RAUs in motor-picocells that are deployed along the motorway at onw dimension in overlapping manner. At the headend part, radio frequency (RF) signals are converted into optical signal by directly modulating a laser diode (LD). The obtained optical signal is carried over the downlink single mode fibre (SMF) to a remote access unit (RAU). On remote site, RAU converts optical signals to RF signal by using a photodiode (PD). RF amplifier will help to provide the required radio coverage. RF circulator is used here to separate transmitted signal from received signal. For uplink transmission, the wireless signal received at the RAU is first amplified and then converted into optical signal by a LD, which, in turn, transported over uplink SMF to the headend.

The second question is co-channel interference involve, because the motor-picocells that belong to the same BS use the same frequency. Time slot distributor (TSD) is introduced here to allocate different time slots to communications at the same frequency over adjoining RAU radio zones, the on-board vehicle transceiver can keep continuous communication over the radio zones while switching the time slot allocated thereto. For example, the time slot can be allocated in such a way that communication over radio zones is always carried out at the same communication frequency. Further, even if all time slots for a certain frequency are occupied, continuous communication can be maintained by switching the communication frequency in use to another frequency.

In this converting processing, most of the parameters in conventional micro cell are kept not to change: The RF in the same group of picocells is the same, and adjacent group of picocells that belong to another micro cell must not use the same RF channel to avoid co-channel interference. Therefore, while a vehicle is running within the same group it does not have to change RF channels. It must change RF channels only when it enters a new group of picocells. While the previous frame structure designed for micro cell is subdivided into frames for the picocells in the group, and a frame is composed of downlink and uplink portion. The size of a frame for a picocell can be made proportional to the traffic demand of the cell.

It should be emphasized here that during a time period for frame i only the corresponding RAUs is activated by the BS in disjoint time period (i.e. frames). Therefore, although one RF channel is employed there is no co-channel interference between cells within a group of picocells. If a vehicle is in non-overlapping area, it will listen to one frame that corresponds to the cell where it is located. While if it is in overlapping area, it will listen to two frames from adjacent picocells. For instance, in Fig. 5 vehicle 1 (V1) receives only frame 1, while vehicle 2 receives frame 1 and 2 since it is in the overlapping area between cell 1 and 2. Moreover, the figure also indicates the fact that a frame can support multiple vehicles as described in cell 3.

In this way, many RAUs can share a single BS and its electrical/optical devices to greatly reduce overall costs. TSD can be put at headend or remote site, where on remote site means all RAUs can share a pair of SMFs for downlink and uplink transmission of the signals, reducing the cost further. Obviously, this system design will...
increase the complexity of each BS, but the number of BSs needed for the whole system is decreased in a large amount.

IV. WIMAX FAST-MOVING NETWORK: CROSS LAYER DESIGN

This section presents the PHY/MAC and Network layer design, subject to effective coverage scheme, adaptive modulation, buffer management scheme and intelligent handover scheme.

A. Effective coverage scheme

When trying to implement the above system structure into a real motorway scenario, we found that conventional BS ranges from several kilometres to tens of kilometres in radius, deploying along motorway at one dimension will lead to large areas of useless coverage on both sides of the motorway where no traffic flow at all. To increase the effective coverage, we have to reduce the cell size, which means more BSs are needed in covering the whole stretch of the motorway and cause the system cost increased in return. Dealing with this dilemma, Wimax fast-moving network (WiFan) effective coverage scheme is involved as below (c.f., Fig. 3)

As we have mentioned above, WiFan-ECS converts conventional WiMAX cell from several kilometers to several tens of kilometers in radius, applying to motorway scenario a fixed radius at one dimension will inevitably lead to large areas of unused coverage. Even the cell size is reduced to 500m in radius, comparing with a six lane of motorway normally not more than 32m in width, there are still hundreds of thousand square meters of unused covering areas on each side of the motorway where no vehicular traffic flow at all.

The effective parameter, namely CovR, is defined as effective coverage of motorway access networks as follows:

\[ Cov_R = \frac{Area_{motor-way}}{Area_{BS}} = \frac{2\pi R^2 \sin \theta}{\pi R^2} \]  

where \( Area_{motor-way} \) is the wireless signal coverage on the motorway, \( R \) is radius of the BS, \( \theta \) is central angle. Note that \( \theta \) is measured by the width of the motorway and radius of the conventional cell.

A flat approach to conventional WiMax cell is hereby adopted by narrowing the cover of motorway on both sides while stretching the cover along motorway. One of the methods to do this is to divide conventional BS into a number of motor-picocells and deploy them along the motorway. Suppose the area does not change after the converting, e.g., the processing capacity of BS is the same as before but can be fully utilized through this converting. However, we must keep it in mind that a certain overlapping areas are needed between motor-picocells so as to guarantee vehicles with an ongoing communication session not to be dropped. In this context, we can get an equation below:

\[ \pi R^2 = n \pi r^2 - 2(n - 1) \left( \frac{\pi r^2 \alpha}{360} - \frac{1}{2} r^2 \sin \alpha \right) \]  

where area of conventional cell equals to the sum areas of motor-picocells, \( R \) is radius of conventional cell, \( r \) is radius of motor-picocell, and \( \alpha \) is the angle for motor-picocells. In this context, the enhanced effective coverage, \( Cov_{e} \), is defined as

\[ Cov_e = \frac{d(2nr - 2(n - 1)(r - 1/2\sqrt{4r^2 - d^2}))}{\pi R^2} \]

where \( n \) is the number of the motor-picocells (size of cluster), \( r \) is radius of the motor-picocells, \( d \) is the width of the motor-way. Finally, we abstract the general analytic solution as

\[ Cov = \frac{D(2nr - 2(n - 1)(r - 1/2\sqrt{4r^2 - D^2}))}{\pi R^2} \]

where \( l \) is the guarantee distance of the transiting, \( D = d + \Delta d \), \( \Delta d \) is the guarantee distance, \( r = (D^2 + l^2)/(4l) \) and \( n = (\pi R^2 - \pi r^2\alpha/180 - r^2 \sin \alpha)/(\pi r^2 - \pi r^2\alpha/180 - r^2 \sin \alpha) \).

B. The PHY wireless channel

In order to find out the optimum threshold \( T \) of the buffer management, it is vital to approach a cross-layer design where the relation between buffer management of network layer and the transmission, service rate & error packet rates of the PHY layer must be specified under the different modulation schemes. The adaptive modulation (AM) is used in conjunction with the ARQ to obtain the spectral efficiency (i.e. maximize transmission rate under QoS constraint). For analytical purpose, we assume the M-QAM signalling over the Additive White Gaussian Noise (AWGN) channel.

We now attempt to achieve the transmission rate, denoted by \( R_t \) (packets/s), and the packet error rate (PER), denoted by \( R_e \) (packets/s), with respect to each modulation scheme. Denoting \( R_s \), \( N_b \) and \( B \) as the symbol rate, the packet length and the number of bits per symbol, respectively, (note that \( B = \log_2 M \)), then we have \( R_t = R_s B/N_b \). \( R_e = R_t P_e \), where \( P_e \) is the probability of packet error of the M-QAM scheme over the AWGN channel and can be obtained via the bit error rate \( P_b \) [11] as follows:

\[ P_p = 1 - (1 - P_b)N_b/B \]

(5)

\[ P_b = 2(1 - 1/\sqrt{M})Q(\sqrt{3SNR/(M - 1)}) \]

(6)

Here, \( Q(x) = \frac{1}{\sqrt{\pi}} \int_{x}^{\infty} e^{-t^2/2} dt \) and \( SNR \) is the signal to noise per symbol.

For low modulation scheme (i.e. \( M \) is small), it is obvious that the transmission rate is \( R_t \) low. However, the PER \( R_e \) is also small, which guarantees that the retransmission requests are less often. If the higher modulation scheme is employed, the reversed situation is observed. Thus an adaptive modulation scheme can be employed depending on the channel quality and the QoS constraint.

C. Adaptive modulation with QoS constraint

The adaptive modulation is employed to maximize the throughput (i.e. transmission rate) given a QoS constraint. For convenience, we assume QAM is considered. Assume that there are two modulation schemes which can be adaptively switchable, denoted by \( M_1 \)-QAM
and $M_2$-QAM where $M_1$ and $M_2$ are their numbers of elements of the constellation set ($M_1 < M_2$).

Under the QoS constraint that the PER $P_p \leq \alpha$, from (5) and (6) we can find the corresponding SNR thresholds $\gamma_{M_1}$ and $\gamma_{M_2}$ for two modulation schemes $M_1$-QAM and $M_2$-QAM, respectively. This means that, to obtain $P_p \leq \alpha$, the minimum SNR required is $\gamma_{M_1}$ for $M_1$-QAM and $\gamma_{M_2}$ for $M_2$-QAM. Note that the higher order modulation, the higher transmission rate and, however, the worse PER performance obtained. Assuming the current modulation scheme is $M_1$-QAM, depending on the channel quality (i.e. SNR) the adaptive modulation can be explained as follows:

1) If $SNR < \gamma_{M_1}$: The modulation scheme will be switched to a lower order, e.g., $M$-QAM where $M < M_1$.
2) If $\gamma_{M_1} \leq SNR < \gamma_{M_2}$: The modulation scheme will remain as it is (i.e. $M_1$-QAM).
3) If $SNR \geq \gamma_{M_2}$: The modulation scheme will switch to the higher order modulation $M_2$-QAM.

D. ME Analysis of the GE/GE/1/N/HoL/CBS queueing Systems

This section highlights the ME methodology, as applied to the analysis of the GE/GE/1/N/HoL/CBS queueing systems. Moreover, further details on the mathematical proofs associated with key analytic GE-type results can be found in [14, 15].

GE-Type Distribution: The GE-type distribution is of the form [c.f., 12, 13]

$$F(t) = P(X \leq t) = 1 - e^{-\tau t}, \tau = 2/(1 + C^2), t \geq 0 \quad (7)$$

where $X$ is an interevent time random variable and $\{1/\tau, C^2\}$ are the mean and squared coefficient of variation (SCV) of the interevent times, respectively.

The GE distribution has a counting compound Poisson process (CPP) with geometrically distributed batch sizes with mean $1/\tau$. It may be meaningfully used to model the inter-arrival times of bursty multiple class mobile connections with different minimum capacity demands. Note that an IP packet length distribution is known to be non-exponential and should at least be described by the mean, $1/\nu$, and SCV, $C^2$. This is because IP packets are restricted by the underlying physical network, such as 3G and WiMAX, and thus, they have different packet lengths, typically 100 bytes and 40 bytes, respectively.

Maximum Entropy Formalism: The principle of maximum entropy (ME) (c.f., [12]) provides a self-consistent method of inference for characterizing, under general conditions, an unknown but true probability distribution, subject to known (or, known to exist) mean value constraints. The ME solution can be expressed in terms of a normalizing constant and a product of Lagrangian coefficients corresponding to the constraints. In an information theoretic context, the ME solution is associated with the maximum disorder of system states and, thus, is considered to be the least biased distribution estimate of all solutions satisfying the system’s constraints. Major discrepancies between the ME distribution and an experimentally observed (c.f., [12]) or stochastically derived (c.f., [13]) distribution indicate that important physical or theoretical constraints have been overlooked. Conversely, experimental or theoretical agreement with the ME solution represents evidence that the constraints of the system have been properly identified. Further information on ME formalism and queueing system can be found in Kouvatos [13].

Notation:
For each class $i$ ($i = 1, 2, \ldots, R, R > 1$) let $\{1/\lambda_i, C_i^2\}$, $\{1/\mu_i, C_i^2\}$ be the mean and SCV of the interarrival and service time distributions, respectively.
F. Intelligent handover scheme

Based on the discussion above, we propose an MAC protocol for the system. Design goals of the MAC include a support of fast handover and capability of adaptive resource allocation of high throughput based on dynamic TDMA. The proposed architecture assumes a centralized MAC entity located at the CS offering a reservation-based, collision-free medium access (see Fig.5).

![Motor-picocells frame structure of BS and sub-frame](image)

Each frame belongs to a certain RAU begins with “beacon” field generated at the BS that consists of RAU identification (ID) number and slot assignment map specifying the start slot position and length for each vehicles. The following field is “reservation slots” which is accessed by vehicles that have not yet reserved any slots but have the data to transmit in contention-based way. The results of reservation trial in the previous frame is broadcast in the "broadcast" field, which is followed by downlink and uplink slots assigned to each vehicles as specified in the slot assignment map. In the uplink slot, there is a handover indication area consisting of four bits for fast handover within the same BS and between different BSs.

Handover within the same BS: As all RAUs of a BS utilize the same RF channel, a vehicle entering the overlapping region between RAUs begins to receive two beacons, each containing a different RAU-ID during an allocated frame time. The vehicle sends in turn the BS a handover request by setting the "intra-handover flag" then the BS reserves bandwidth for it in the next picocell and releases bandwidth used by the vehicle in the old cell. It should be noted that resources to handover a connection from one RAU to its successor RAU are always available as the centralized MAC may adjust (i.e. shorten) the frame length of the RAU the vehicle is leaving and hence can increase the frame duration of the successor RAU in order to provide the vehicle with the required resources.

Handover between different BSs: On a highway scenario, vehicle can only travel on one dimension with two opposite directions. A direction parameter was introduced here to notify BS that vehicles in each RAU are running in different directions. After comparing the new RAU-ID with the old one, the vehicle will set the direction parameter to "1" if the ID works in an increasing base. Otherwise, it will be set to "0". Apparently, the BS knows the location of its first RAU and last RAU, which are indicated in RAU-ID as well. When a vehicle's direction parameter is "1" and receives the beacon of the last RAU, it sets it third bit to "1", which means it enters the last RAU of the BS, telling CS to inform the adjacent BS to prepare the handover resources. At the same time, the vehicle will begin to scan RF channels in the next BS. If it receives the new RF channel, it sends a handover request by setting the forth bit to "1" for inter-BS handover. If the request to the new BS is successful and there is enough bandwidth in the new BS, the vehicle can continue its communication session; otherwise, the request is dropped. Thus, unlike intra-BS handover successful inter-BS handover involves not only changing RF channels but also bandwidth management. Through setting the pre-notify bit in advance, the CS may give the vehicle requesting handover higher priority than new connection requests. Similar process is applied when direction parameter is "0" and RAU-ID is the smallest, which means the vehicle will request handover between BSs in another end.

V. Numerical Results

This section presents typical numerical results to (i) illustrate the credibility of the proposed EMS (ii) Simulation results from PHY layer (iii) to assess ME solution and the impact of GE-type bursty traffic on network performance. Note that the Java programming language was used to carry out the simulation analysis of the QNMs of Figure 4 at 95\% confidence intervals.

Figure 6 illustrates the comparative results between the conventional and our effective schemes. It is seen that, in our scheme, the utilisation of the EMS is increased by about 60\% compared to the conventional scheme with the variation of the arrival and service rates.
GE/GE/1/N/HoL/CBS with threshold (T), illustrated by ME analytic solution (AN) and simulation solution (SIM), is much better than the generical GE/GE/1/N/HoL/CBS.

![Graph 1](image1.png)

Fig. 7. Effect of traffic variability on the utilization of 4-QAM

Figures 8 and 9 present the ME analytic results with various channel conditions and modulation schemes. In Fig. 8 (16-QAM), we can achieve the value of 6 as the optimum threshold of the buffer size of 16 with various arrival rates and utilization. On the other hand, with 4-QAM modulation, we can obtain the optimum threshold of 4 under the same conditions in Fig. 8. So our algorithm could attribute to network designer to figure out the optimum thresholds with various channel conditions.

![Graph 2](image2.png)

Fig. 8. Effect of threshold variability on the utilization of 16-QAM

![Graph 3](image3.png)

Fig. 9. Effect of threshold variability on the utilization of 4-QAM

VI. CONCLUSION AND FUTURE WORK

Central controlled radio fibre architecture of access network is an applicable option in addressing motorway broadband communication for high speed vehicles. Through the combination of RoF and TSD, the effective coverage of wireless signal could be improved greatly, while co-channel interference could be avoided. Four parameters are involved for intra-BS handover and inter-BS handover to simplify the handover procedure on motorway scenario and make the fast handover to be feasible. This system design provides us two apparent advantages: 1) through RoF, the conventional size base station is converted into a number of micro size base stations to increase data rate, and make the cell size to match with highway scenario: long and narrow cover areas. 2) most of the control systems are centralized to propose a promising cost-effective solution to meet ever increasing user bandwidth and wireless demands. Performance evaluation of resource management schemes is now under way, and preliminary results show the proposed architecture is efficient.

REFERENCES


