A Study on Link Adaptation Techniques for IEEE 802.11bd Based eV2X Communications

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Abstract—The ultra-high reliability is an essential requirement for enhanced vehicle-to-everything (eV2X) use cases. In order to ensure the desired reliability in a time-varying channel, link adaptation is required. Therefore, the current and upcoming technologies use adaptive modulation and coding (AMC) schemes. By using AMC, the reliability and data rates could be adapted according to the channel conditions. To further improve reliability, concepts like multi-connectivity could also be used. In multi-connectivity, redundant data can be transmitted using multiple simultaneous links and combined at the receiver to improve reliability. However, this requires link adaptation in both numbers of multiple links and AMC. In this paper, we evaluate different link adaptation schemes for IEEE 802.11bd based on single-link and multi-connectivity communications. For single-link communications, we generate channel quality indicators (CQI) based on various signal-to-interference-plus-noise ratio (SINR) mapping techniques, e.g., exponential effective SINR mapping (EESM), received bit information rate (RBIR), and recently proposed enhanced EESM (eEESM). The performance of these schemes is evaluated in terms of achieved reliability and data rates. Results show that eEESM achieves close to optimal performance. In the case of multi-connectivity, different MCS and link adaptation schemes are evaluated. It is shown that joint adaptation of MCS and the number of links deliver better performance in terms of data rates and link utilization.

Index Terms—Adaptive Modulation and Coding, IEEE 802.11bd, Link adaptation, Multi-connectivity, 5G and beyond

I. INTRODUCTION

In the recent decade, vehicle-to-everything (V2X) communications gained huge interest due to their immense potential in improving road safety. It can reduce traffic jams, enable autonomous driving, increase road safety, and can provide an alternative emergency communications system in natural disasters. The IEEE 802.11p was the first standard introduced in 2010 [1] to enable direct communication between vehicles for the exchange of cooperative awareness messages (CAM). Over the period, on one hand, autonomous driving and enhanced V2X (eV2X) use cases gained more interest, on the other hand, new state-of-the-art wireless technologies are developed. To meet the demand for eV2X use cases and upgrade V2X access, the IEEE 802.11 group is working on next generation V2X (NGV) standard, i.e., IEEE 802.11bd [2]. It is expected that IEEE 802.11bd will greatly improve the performance compared to IEEE 802.11p [3] by using new physical layer (PHY) and medium access control (MAC) techniques. Assuming that it defines a feedback channel for acknowledgment and channel quality indicator (CQI) reporting, link adaptation schemes could be used to optimize its data rates, reliability, and coverage.

In modern wireless communication systems, various applications demand certain quality of service (QoS) for reliable operations which require maintaining a minimum received signal-to-interference-plus-noise ratio (SINR). However, the signal strength varies over time due to multipath fading, Doppler, and path loss. To ensure QoS under varying channel conditions different parameters can be adapted such as transmitted power, and modulation and coding scheme (MCS). By adapting the transmission power chance of interference from other users also increases. Alternatively, MCS adaptation deals with variable data rates instead of power i.e. its function is to adjust the data rates with changing channel conditions. Most of the current wireless systems i.e., LTE, NR, IEEE 802.11 p/n/ac/ad/ax support multiple MCSs, each providing different throughput and reliability levels. Based on the CQI, a user equipment (UE) can adapt its MCS dynamically, which at that particular time provides better throughput or reliability. This procedure of link adaptation is also known as adaptive modulation and coding (AMC).

In literature, various rate adaptation methods are investigated in the past decades. Many of these studies consider adapting link based on the past statics such as tracking the past successful/unsuccesful transmissions [4]–[7]. However, these methods are not effective under rapidly changing channel conditions due to outdated CQI. Moreover, MCS selection per subcarrier or per resource block (RB) is not possible, which could be used to optimize throughput under frequency selective fading. Some other approaches consider link adaptation based on the instantaneous received signal strength or SINR [8]–[11]. This metric provides better performance compared to the previous approaches, as it enables rapid adaptation of MCS in a time-varying channel. However, in wideband orthogonal frequency division multiplexing (OFDM) systems each subcarrier could have variable SINR under frequency selective fading. In this case, the link is either adapted per subcarrier or based on the effective SINR of all subcarriers. The effective SINR of a fading channel is additive white Gaussian noise (AWGN) equivalent SINR and represents the joint symbol error rate (SER) of all subcarriers. Moreover, in the case of multi-connectivity, CQI represents all connected links to adapt the MCS and the number...
of parallel links. Therefore, the effective SINR not only needs to represent the performance of a link but the joint performance of all connected links.

The state-of-the-art techniques used for effective SINR mapping are exponential effective SINR mapping (EESM) and receive-bit-mutual-information-rate (RBIR). In [12], authors used EESM based mapping for link adaptation in heterogeneous networks of IEEE 802.11n and LTE. Further, in [13], the authors proposed RBIR based mapping to evaluate the performance of IEEE 802.11ax. Besides, several other investigations have also used these mapping techniques for link adaptation [14]–[16]. Recently, in [17], a new technique enhanced EESM (eEESM) is proposed and its mapping performance is evaluated against EESM and RBIR for a range of technologies. The presented results reveal that eEESM outperforms EESM and RBIR for all considered technologies. Nevertheless, all the above-mentioned studies only model single-link communications in specific channel conditions. The multi-connectivity communications and performance modeling in V2X communications were not considered. In addition, IEEE 802.11bd uses dual carrier modulation (DCM) and PHY performance with this option has never been abstracted. Therefore, to the best of our knowledge, this paper provides the first comprehensive study on link adaptation techniques in the context of IEEE 802.11bd and multi-connectivity.

In this paper, we model IEEE 802.11bd based link-level simulator to evaluate various link adaptation techniques. The communication between two vehicles is realized using single-link and multi-connectivity communications. We abstract the link-level performance of IEEE 802.11bd using different effective SINR mapping techniques. This also includes the DCM and multi-connectivity communications with maximum ratio combining (MRC). Then, we evaluate the link adaptation performance of these mapping techniques compared to the optimal link adaptation. In single-link communications, we compare the performance of various link adaptation schemes in terms of achieved data rates and reliability. For the case of multi-connectivity, we consider various link adaptation schemes to adapt MCS and the number of links. Subsequently, we propose an algorithm for joint adaptation of MCS and number of multiple links to enable ultra-reliable communications. Even though, in this paper only IEEE 802.11bd based multi-connectivity is considered, the developed algorithms are also valid for other technologies.

## II. OVERVIEW OF IEEE 802.11BD (DRAFT)

This section provides an overview of the current draft status of the 11bd workgroup. The new features that have been already agreed or under discussion are described in the framework specification document [18]. It defines 10 MHz PHY and an optional 20 MHz PHY, which are two times down clock version of IEEE 802.11ac 20 MHz and 40 MHz PHY, respectively. This also implies that low-density parity check (LDPC) channel coding and higher-order MCS are adopted as well. This will improve the reliability and data rates compare to 802.11p. To improve the performance under doubly-selective channels, the high-density midambles are adopted from 802.11ax. Three midambles periodicities are defined i.e., 4, 8, or 16 OFDM symbols to adapt according to the channel selectivity. In addition, the DCM which is also known from 11ax is defined here as MCS 10 [18]. In DCM, system bandwidth is divided into two halves, each carrying the duplicated data. On the receiver side, both redundant data versions are combined using soft MRC combining. This reduces outage probability by exploiting the frequency diversity. Furthermore, to enhance data rates it supports two spatial streams for unicast transmission as an optional feature. Besides the current intelligent transportation system (ITS) at 5.9 GHz band, optional support for mmWave 60 GHz band has been proposed to exploit high bandwidths.

Due to backward compatibility and coexistence issues, the IEEE 802.11bd frame structure is similar to IEEE 802.11p with an additional NGV header. To increase transmission reliability, the introduction of acknowledgments and re-transmissions are under discussion. The link-level simulator considered in this paper only model performance with 10 MHz PHY at 5.9 GHz with one spatial stream. Table I provides an overview of various MCS options and consequently achievable data rates for a payload \((P_b)\) of 300 bytes. The given data rates are calculated as,

\[
\text{Data Rates} = \frac{P_b \times 8}{T_{tx}},
\]
where $T_{tx}$ is total packet duration defined as

$$T_{tx} = t_{pre} + t_{AIFS} + t_{sym} \cdot n_{sym} + t_{sym} \cdot n_{ma}, \quad (2)$$

where $t_{pre}$ is the preamble duration (80 $\mu$s for 11bd), $t_{AIFS}$ is the arbitrary inter-frame space (32 $\mu$s for priority data), $t_{sym}$ is the OFDM symbol duration (8 $\mu$s), $n_{sym}$ denotes the number of OFDM symbols required to transmit $P_{tx}$, and $n_{ma} = \lfloor n_{sym} - 1/t_{ma} \rfloor$ is the number of midambles in the packet, where $t_{ma}$ is the midamble periodicity (8 OFDM symbols for MCS 0-4 & 10, and 4 OFDM symbols for MCS 5-9). In this paper, we also proposed multi-connectivity operation with IEEE 802.11bd to further enhance its reliability under harsh channel conditions.

### III. SYSTEM MODEL

A vehicular communications scenario is considered consisting of a link management entity (LME) and $M$ access points (APs) $(AP_i, \forall i \in M = \{1, 2, \ldots, M\})$ serving to different user equipment’s (UEs) $(UE_i, \forall i \in U = \{1, 2, \ldots, U\})$, as shown in Fig. 1. The LME is responsible to assign required number of resources to UEs for vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communications. To evaluate performance of link adaptation techniques IEEE 802.11bd based link-level simulator is used. The following assumptions are valid for further analysis. All APs and UEs have a single TX/RX antenna per RF front-end and are operating at different frequencies. The channel coefficients on all links are independent, identically distributed (iid). This is particularly true when APs are sufficiently spaced apart and operating at different frequency bands in a rich scattering environment.

#### A. Single-Link Communications

In the case of single-link, direct communication between two departing vehicles is modeled. Let $N$ denote the number of OFDM subcarriers and $h_n$ being the channel coefficient at $n$-th subcarrier. The single-link received SINR per subcarrier ($\gamma_{sl,n}$) can be defined as

$$\gamma_{sl,n} = \frac{P_{tx} \cdot G_{tx} \cdot G_{rx}}{L_0 \cdot d^\alpha \cdot \sigma_{NF}^2 \cdot \sigma_{n+i}^2} |h_n|^2, \quad (3)$$

where $P_{tx}$ is the transmit power in watts, $G_{tx}$ is the transmit antenna gain, $G_{rx}$ is the receive antenna gain, $L_0$ is the path-loss at a reference distance of 1 m, $d$ is the distance in meters between transmitter and receiver, $\alpha$ is the path loss exponent, $\sigma_{NF}^2$ is the noise figure of the receiver, and $\sigma_{n+i}^2$ is the noise plus interference power.

In the case of MCS 10 (where DCM is used) data is combined from the upper and the lower half of subcarriers using soft MRC combining. Let $N = N/2$ is the number of lower half of subcarriers and $n = 1, \ldots, N$ is the index. The received SINR after combining is given as

$$\gamma_{sl,n} = \frac{P_{tx} \cdot G_{rx} \cdot G_{nx}}{L_0 \cdot d^\alpha \cdot \sigma_{NF}^2 \cdot \sigma_{n+i}^2} (|h_n|^2 + |h_{n+N}|^2). \quad (4)$$

#### B. Multi-Connectivity Communications

In the case of multi-connectivity, communication between a vehicle and infrastructure is assumed. The APs transmit duplicate data to UE through parallel connected links. For the sake of simplicity, it is assumed that all assigned links have equal average received SINR. It means the average received SINR of all connected links is same but subcarrier could have variable SINRs. This could be achieved by controlling the transmitted power of links at different distances. Let $N$ denotes the number of OFDM subcarriers, $L$ denotes the number of simultaneously connected links, and $h_{l,n}$ denotes the channel coefficient of $l$-th link and $n$-th subcarrier. Similar to (3), the instantaneous SINR at $n$-th subcarrier of $l$-th link is represented as

$$\gamma_{mc,n} = \frac{P_{tx} \cdot G_{rx} \cdot G_{nx}}{L_0 \cdot d^\alpha \cdot \sigma_{NF}^2 \cdot \sigma_{n+i}^2} |h_{l,n}|^2. \quad (5)$$

The received symbols from multiple links can also be combined using diversity combining techniques, e.g., selection combining (SC) and MRC, to improve reliability. In this paper, we consider per subcarrier-wise combining of multiple links using MRC combining. The subcarrier SINR after MRC combining can be written as

$$\gamma_{mc,n} = \sum_{l=1}^{L} \gamma_{mc,n,l}. \quad (6)$$

The combined SINR now can be treated likewise to single-link communications for effective SINR mapping. It is important to note that in the case of multi-connectivity DCM option (MCS 10) is not used to avoid the redundant use of frequency diversity.
where $N$ is the total number of data symbols, $\gamma_n$ is the post-processing received SINR at $n$-th symbol (e.g., obtained form (3) or (6)) and $\beta$ is the optimization parameter. The optimum value of $\beta$ is the least square fit that minimizes the mean square error (MSE) between effective SINR and AWGN SNR [21]. Thus, we can write

$$\beta_{opt} = \arg \min_\beta \left| \gamma_{AWGN} - \gamma_{eff}(\beta) \right|^2.$$  (8)

### IV. Effective SINR Mapping

As mentioned earlier, in the case of frequency selective fading, the received symbols in a packet could have different SINRs. To estimate the joint error probability of these symbols, effective SINR mapping is required. The effective SINR is an AWGN equivalent SNR at which fading channel performance becomes equivalent to the AWGN channel. By doing so, the performance of a fading channel can be evaluated using pre-generated AWGN lookup tables. This is particularly necessary for coded modulations, which don’t have closed-form expressions for SER analysis. The above procedure can be summarized as follows:

1) Generate SINR vs. PER lookup table for each MCS under AWGN channel conditions, as given in Fig. 2.
2) Calculate / estimate fading SINR of received symbols.
3) Map the received SINRs to effective SINR using effective SINR mapping techniques.
4) Now estimate the PER performance using lookup tables generated in step 1.

To obtain effective SINR various mapping techniques exist, which are being introduced here. The link adaptation procedure is explained in Fig. 3.

#### A. Exponential Effective SINR Mapping (EESM)

The EESM is derived from the upper bound on SER using Chernoff bound [19]. The generalized expression for effective SINR ($\gamma_{eff}$) in the case of EESM can be written as [20]

$$\gamma_{eff} = -\beta \ln \left( \frac{1}{N} \sum_{n=1}^{N} \exp \left( -\frac{\gamma_n}{\beta} \right) \right),$$  (7)

where $N$ is the total number of data symbols, $\gamma_n$ is the post-processing received SINR at $n$-th symbol (e.g., obtained form (3) or (6)) and $\beta$ is the optimization parameter. The optimum value of $\beta$ is the least square fit that minimizes the mean square error (MSE) between effective SINR and AWGN SNR [21]. Thus, we can write

$$\beta_{opt} = \arg \min_\beta \left| \gamma_{AWGN} - \gamma_{eff}(\beta) \right|^2.$$  (8)

#### B. Received Bit Information Rate (RBIR)

The RBIR calculates effective SINR using mutual information of the received symbol [13]. The effective SINR expression using RBIR is written as

$$\gamma_{eff} = \beta \Phi^{-1} \left\{ \frac{1}{N} \sum_{n=1}^{N} \Phi \left( \frac{\gamma_n}{\beta} \right) \right\},$$  (9)

where $\Phi$ is the mutual information per symbol, defined in [17, eq. 35].

#### C. Enhanced EESM (eEESM)

In [17], eEESM is derived from a tighter approximation of SER, given by $Q(x) \approx \frac{1}{\sqrt{2\pi(x^2+1)}} \exp \left( -\frac{x^2}{2} \right)$ [22, eq. (21)]. By using the approximation effective SINR expression is written as

$$\gamma_{eff} = \frac{\beta}{2} \left\{ W \left[ \exp(0) \left( \frac{1}{N} \sum_{n=1}^{N} \frac{1}{\sqrt{2\pi(n^2+1)}} \exp \left( -\frac{\gamma_n}{\beta} \right) \right) \right] - 1 \right\}.$$  (10)

where $W(\cdot)$ is the Lambert-W function defined as $W(x e^x) = x$ [23].

In Table I, the default values of $\beta$ are listed for the above-mentioned SINR mapping techniques.

### V. Evaluation Results

To evaluate the performance of various link adaptation schemes, a vehicular communication scenario is considered, as shown in Fig. 1. The channel characteristics are modeled...
using urban crossing non-line of sight (NLOS) channel model proposed by 11bd task group in [24]. To meet the QoS requirements under the time-varying channel MCS can be adapted, assuming that a feedback channel exists to report CQI. The main goal here is to optimize data rates without violating certain outage probability (i.e., PER). The minimum SINR threshold is selected for the next transmission. The effective SINR is calculated and compared against the threshold, then the highest MCS with the SINR threshold lower than the effective SINR is selected for the next transmission. This procedure is illustrated in Fig. 3 and relevant simulation results are depicted in Fig. 2. Moreover, the achievable data rates for these MCSs are also provided in the same Table. The link adaptation is achieved as follows: for each received packet the effective SINR is calculated and compared against the threshold, then the highest MCS with the SINR threshold lower than the effective SINR is selected for the next transmission. This procedure is illustrated in Fig. 3 and relevant simulation parameters are listed in Table II.

A. Single-Link Communications

In single-link communications, the data is transmitted or received from one source or destination. Therefore, the main focus of the investigation is to evaluate the ability of various link adaptation techniques to select an optimal MCS. Following schemes are considered for MCS selection.

Ideal MCS selection (IMS): The IMS is obtained from link-level simulations by calculating data rates and reliability for all MCSs and choosing one which delivers the highest data rates while fulfilling the desired reliability. In other words, it is an upper bound on the performance. 

Scheme I: Select an MCS based on the instantaneous average received SINR or average SINR mapping (ASM).

Scheme II: Choose MCS based on the effective SINR obtained using EESM, i.e., Eq. (7).

Scheme III: The effective SINR obtained using RBIR, i.e., Eq. (9).

Scheme IV: The effective SINR is calculated using eEESM, i.e., Eq. (10).

The performance of these schemes is evaluated in terms of data rates and outage probability.

1) Data Rates: The achieved data rates are plotted in Fig. 4 for PER < 10^{-1} and PER < 10^{-3}. In both cases, it can be observed that Scheme IV (eEESM) outperforms all other schemes, even though, the difference compared to Scheme III (RBIR) is marginal. The performance of Scheme IV is close to the ideal MCS selection (IMS) scheme. This also reflects that the effective SINR obtained using eEESM is the most accurate compared to the other schemes. The worst performance is in the case of Scheme I (ASM), which chooses the MCS based on the instantaneous received SINR. This scheme overestimates the effective SINR, as a result, chooses a higher MCS which results in an outage considering the QoS requirements.

Fig. 4. Achieved data rates using various link adaptation schemes with single-link communications

Fig. 5. Outage probability of various link adaptation schemes with single-link communications
contrast. Scheme II (EESM) performs slightly better, but it also overestimates the effective SINR due to the mapping error. Furthermore, by comparing 4(a) with Fig. 4(b), it could be observed that the data rates decreases with the increase in required reliability. This is due to the fact that higher SINR is required for each MCS to ensure PER < 10^{-3} compared to PER < 10^{-1}.

2) Outage Probability: Besides data rates, another important parameter is the outage probability / link-drop probability. It can be defined as the probability (P_{out}) that the required QoS cannot be guaranteed, either due to wrong MCS selection or due to link-outage. The link is said to be in an outage when the received SINR is too low to meet the required reliability, even with the lowest possible MCS. Outage probabilities of link adaptation schemes are plotted in Fig. 5 for both applications (i.e., PER < 10^{-1} and PER < 10^{-3}). For the optimal MCS selection case, the outage probability is 0 for lower distance (d < 220 m) and increases with the increase in distance due to link-outage. The lowest outage probability is achieved by Scheme IV due to accurate MCS selection. Among other schemes, Scheme III has a lower outage probability followed by Scheme II, while Scheme I being the worst. Scheme I has almost similar performance for both reliability levels as in this case effective SINR is simply equal to the average SINR and has no impact on reliability threshold. Moreover, the outage probability of Scheme III and Scheme IV is overlapping for applications that require higher reliability. This is due to the decrease in mapping error for lower values of PER [17].

B. Multi-Connectivity Communications

In 5G and beyond communications, multi-connectivity is being considered as an enabler for ultra-reliable communications under harsh channel conditions. Therefore, the following link adaptation schemes are investigated here:

- **Scheme I**: The MCS is fixed, which means it uses the lowest possible MCS and selects the required number of links depending on the path loss or distance to ensure a PER < 10^{-3}.

- **Schemes II**: The MCS is fixed similar to Scheme I, but the number of links could be adapted depending on the instantaneous effective SINR (i.e., small scale fading). The optimization goal here is to use a minimum number of parallel links to ensure a PER < 10^{-3}.

- **Schemes III (proposed)**: Both the MCS and number of links can be adapted depending on the instantaneous effective SINR, as elaborated in Algorithm I. The optimization goal here is two-fold: use the minimum possible number of links to ensure a PER of 10^{-3}, and optimize data rate by selecting appropriate MCS.

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Algorithm 1: Scheme III (MCS and number of links selection for each transmission)

input : L, d, \( \{\gamma_{MC}^{\min}, \gamma_{MC}^{1}, \cdots, \gamma_{MC}^{9}\} \), and H of \( L \times N \)

output: MCS_{index} and L for next transmission

1. calculate \( \gamma_{MC} \) from (6) for \( L \) and \( L - 1 \)
2. obtain \( \gamma_{EESM}^{L-1} \) and \( \gamma_{EESM}^{L} \) from (10)
3. if \( \gamma_{EESM}^{L-1} < \gamma_{MC}^{\min} \) then
   4. \( L = L - 1 \); /* release a link */
   5. go to step 1
4. else if \( \gamma_{EESM}^{L} \leq \gamma_{MC}^{\min} \) then
   7. \( L = L + 1 \); /* request a link */
   8. go to step 1
9. else
   10. \( MCS_{index} = \max \{ \gamma_{MC} \geq \min \{ \gamma_{MC}^{\min}, \gamma_{MC}^{1}, \cdots, \gamma_{MC}^{9}\} \} \); /* MCS selection */
11. end
```

To obtain the effective SINR, eEESM is used here, since it outperforms other SINR mapping techniques. The performance of these schemes is compared in terms of average data rates and the utilized number of simultaneous links. It is important to mention that the DCM option is not used for the case of multi-connectivity to avoid the redundant use of frequency diversity.

1) **Data Rates**: The average data rates for considered schemes are plotted in Fig. 6(a). Scheme I and II use the lowest
MCS, therefore, data rates are equal to the spectral efficiency of MCS0. In contrast, scheme III considers MCS adaptation as well, hence data rates are higher in this case. However, at a higher distance, data rates are almost equal to other schemes. This is due to the decrease in average SINR per link since it is assumed that all links have the same average received SINR. As a result, for \(d > 600\) m the average SINR is close to 0 dB. Therefore, the additional SINR required to use higher-order MCS is not often available. Nevertheless, if links with different average received SINR is considered Scheme III is expected to take even more advantage by adapting MCS.

2) Number of Links: In Fig. 6(b), the average number of links required to ensure a PER of \(10^{-3}\) are plotted. Results depict that Scheme II and III require on average fewer links than Scheme I. Both Scheme II and III adapt the number of links depending on the instantaneous effective SINR, as a result, fewer links are used if the link quality is good. Although Scheme III adapts the MCS in addition to the number of links, the average number of used links is the same as in the case of Scheme II. This is due to the optimization criteria, which only adapts MCS when a lower order multi-connectivity cannot ensure reliability. In other words, the proposed scheme achieves higher data rates by utilizing the same or lower number of links compared to other schemes.

VI. CONCLUSIONS

In this paper, we studied different link adaptation schemes for IEEE 802.11 bd based single-link and multi-connectivity communications. To evaluate the performance of various link adaptation techniques, a IEEE 802.11 bd link-level simulator is used. In single-link communications, various techniques are used to adapt the MCS in a time-varying channel. The simulation results depict that eEESM outperforms all other techniques in terms of data rates and link-outage probability. The reason behind its better performance is the SINR mapping accuracy, which results in AWGN equivalent performance. Comparatively, other techniques overestimate the effective SINR and hence lead to sub-optimal MCS selection. In the case of multi-connectivity communications, we proposed joint adaptation of MCS and the number of links based on the instantaneous effective SINR. The evaluation results show that higher data rates can be achieved by utilizing the same or lower number of simultaneous links. The proposed multi-connectivity link adaptation algorithm is generic and hence could be extended to other technologies.

REFERENCES


