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Energy and Data Throughput for Asymmetric Inter-Session Network Coding

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Abstract—In this paper we investigate the impact of asymmetric traffic patterns on the energy consumption and throughput in a wireless multi hop network. Network coding is a novel technique for communication systems and a viable solution for wireless multi hop networks. State of the art research is mainly focusing on ideal scenarios with symmetric traffic patterns that are not realistic in a real life scenario. The main contribution of this paper is the investigation of the asymmetric traffic patterns in terms of throughput and energy consumption, and a validation of these results by real measurements on commercial platforms. The outcome of this paper confirms the analytical expression, and the results shows that even with a large asymmetric data rate there is a gain in terms of energy consumption and throughput when network coding is applied in compare to the case when network coding is not applied.

I. INTRODUCTION

Modern wireless devices are capable of building large wireless multi-hop networks and aid each other in passing information to other devices in the network. Previous works have aimed to improve the performance in terms of throughput of such wireless multi hop networks by use of network coding. Network coding was first introduced by Ahlswede et al. [1], who showed that allowing the intermediate node(s) to combine information, can improve system throughput. Katti et. al [2], [3] introduced a practical method dubbed COPE, in which network coding was applied in order to improve network throughput. In COPE, packets from different unicast sessions where XOR'ed together, and forwarded in a single transmission.

Recently, the terms energy saving and green wireless communication have become interesting topics leading to several publications and research projects. In these projects and publications network coding has been considered as an energy efficient information exchanging method [4], [5], [6]. These works propose various techniques and methods that additionally reduce the energy consumption while using network coding. The results from these work shows remarkable gain in terms of energy saving. However, these analytical works require a redesign of the existing IEEE 802.11 standard, or a complete new design of a wireless protocol, to achieve a real life implementation. We believe that in order to design energy efficient wireless protocols for the ad-hoc networking environment, some practical knowledge of the state ofart implementations is required. To realize a practical implemen-

a) Without Network Coding
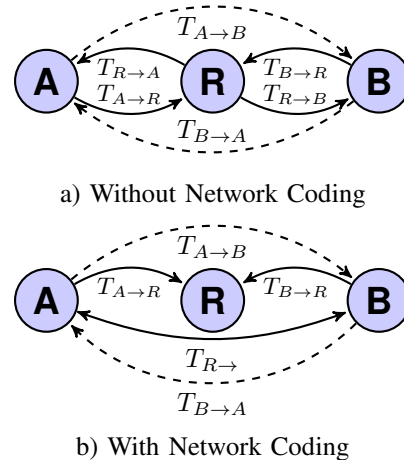

b) With Network Coding

Fig. 1: Alice and Bob scenario with and without network coding. Solid line indicates the activity between the nodes, while the dashed line indicates the end-to-end throughput.

tation of network coding on top of an exciting protocol, we introduced CATWOMAN in one of our previous work [7]. This approach is designed and implemented on top of an existing routing scheme, B.A.T.M.A.N. After our extensive investigation on the throughput of the CATWOMAN approach for the Alice and Bob scenario, we introduced in [8] a model and an energy measurement tool which enables us to measure the energy consumption of each node running CATWOMAN.

In this paper, we present an analytical expression for energy consumption and data throughput in a simple Alice and Bob scenario where asymmetric traffic is considered. This analytical expression is then compared and verified with measurement results using CATWOMAN on of the shelf products: OM1P routers from Open-Mesh Inc.

The paper is structured as follows: In Section II, we present the notations and assumptions which are used as a basis to analyze the energy consumption and throughput of the selected scenario. Our analytical results are compared to our practical measurements in Section III, along with a description of the testbed from which we obtained our measurements. Finally, in Section IV, we conclude on our work on the behalf of our results.

II. ANALYSIS

In the following we describe the notation and assumptions which are used to analyze the Alice and Bob scenario.

A. Notations and Assumptions

TABLE I: Notation

Symbol	Description
i, j	Denotes a node in the scenario, $i, j \in \{A, R, B\}$
X_i	The generated unit less load at node i.
$T_{i \to j}$	The throughput on the link or path from node i to node j.
$T_{i \to}$	The combined throughput on all links from node i.
$T_{\to j}$	The combined throughput on all links into node j.
i_k	Proportion of time where node $i \in \{A, B, R\}$ is in state $k \in \{S, R, I\}$
C	The total measured WiFi capacity on the shared medium.
P_k	Amount of power required when a node is in state k, send (S), receive (R), or idle (I).
E	System energy consumption.

We assume the following:

1) Node A and B, hold infinite data for transmission.
2) Idealized MAC, one node transmit at time, no packet collisions, and the channel capacity is evenly distributed.
3) Performing Network Coding consumes no energy. The coding is based on the simple XOR operation that has very low complexity.
4) Finite queues, at a nodes that receives faster than it is sends packets are dropped with equal probability.

The load at A is always greater than the load at B. No new traffic is generated at R, but it relays the traffic received from A and B respectively, hence:

$$X_R \geq X_A \geq X_B \qquad (1)$$

A node can at maximum send as much data as is generated at that node $T_i \leq X_i$. The sum of the nodes sending activity defines the current usage of the normalized channel capacity.

$$T_{R \to A} + T_{R \to B} + T_{A \to R} + T_{B \to R} \leq 1 \qquad (2)$$

Node i can be in one of three states; Send, Receive, and Idle, and thus:

$$i_S + i_R + i_I = 1 \qquad (3)$$

In the following we analyze the sending and receiving activity of each node in the scenario shown in Figure 1. First we analyze the case without network coding followed by the case with network coding. Based on the activity we define the end-to-end throughput, the system power, and the energy consumed per bit.

B. Without Network Coding

The sending activity at B is upperbounded by the following. Node B can at most send as much data as it generates, hence $T_{B \to R} \leq X_B$. If $X_B \geq \frac{1}{3}$, then by Equation (1) $X_A \geq \frac{1}{3}$ and $X_R \geq \frac{1}{3}$, hence the channel is congested, and B gets it fair share of the channel, as there are three nodes $T_{B \to R} \leq \frac{1}{3}$.

$$T_{B \to R} = \min\left(\frac{1}{3}, X_B\right) \qquad (4)$$

Similar $T_{A \to R} \leq X_A$. The remaining channel capacity is $1 - T_{B \to R}$ which A can at most obtain half of. The reason is that if $X_A \geq \frac{1 - T_{B \to R}}{2}$ then $X_R \geq \frac{1 - T_{B \to R}}{2}$ thus the channel is congested and the MAC distributes the remaining capacity evenly between A and R.

$$T_{A \to R} = \min\left(\frac{1}{2}(1 - T_{B \to R}), X_A\right) \qquad (5)$$

R receives data send from A and B.

$$T_{\to R} = T_{A \to R} + T_{B \to R} \qquad (6)$$

As R forwards the data from A and B, $T_{R \to} \leq T_{\to R}$. As $T_{A \to R}$ and $T_{B \to R}$ are known R cannot send more than the remaining channel capacity permits, hence $T_{R \to} \leq (1 - T_{\to R})$.

$$T_{R \to} = \min\left((1 - T_{\to R}), T_{A \to R} + T_{B \to R}\right)$$

Packets are considered to be dropped at R's queue, if the packet arrival rate at R is higher than the packets transmission rate at R, $T_{R \to} > T_{\to R}$. The ratio of the packets received by R that is not dropped is simply $\frac{T_{R \to}}{T_{\to R}}$. Node R, forwards the packets it receives from A to B, and vice versa. Thus the packets transmitted to A depends on the throughout into R from B and the ratio of packets dropped at R.

$$T_{R \to A} = T_{B \to R}\left(\frac{T_{R \to}}{T_{\to R}}\right)$$
$$T_{R \to B} = T_{A \to R}\left(\frac{T_{R \to}}{T_{\to R}}\right) \qquad (7)$$

Thus the end-to-end throughout from A to B is defined by the weakest of the links over which the packets flow:

$$T_{A \to B} = \min(T_{A \to R}, T_{R \to B})$$
$$T_{B \to A} = \min(T_{B \to R}, T_{R \to A}) \qquad (8)$$

C. With Network Coding

When network coding is applied encoding is only performed at R where a packet from both A and B are combined and broadcasted as a single packet. Therefore $T_{A \to R}$, $T_{B \to R}$ and $T_{\to R}$ are the same as in the case without network coding. R sends both coded, $T_{R,NC \to}$, and uncoded $T_{R,UC \to}$ packets. As R combines one packet from A and one from B to create a coded packets that can be coded is bounded by the flow with the lowest rate. The remaining packets are send uncoded from.

$$T_{R\to} = T_{R,\text{NC}\to} + T_{R,\text{UC}\to}$$
$$T_{R,\text{NC}\to} = \min(T_{A\to R}, T_{B\to R}) = T_{B\to R}$$
$$T_{R,\text{UC}\to} = \text{abs}(T_{A\to R} - T_{B\to R}) = T_{A\to R} - T_{B\to R} \quad (9)$$

As $T_{B\to R} \leq T_{A\to R}$ the rate at which packets are send to A and B is:

$$T_{R\to A} = T_{R,\text{NC}\to} = T_{B\to R}$$
$$T_{R\to B} = T_{R,\text{NC}\to} + T_{R,\text{UC}\to} = T_{A\to R} \quad (10)$$

Similar to the case without network coding the end-to-end throughput is defined by the weakest link between the nodes:

$$T_{A\to B} = \min(T_{A\to R}, T_{R\to B})$$
$$T_{B\to A} = \min(T_{B\to R}, T_{R\to A}) \quad (11)$$

D. Power and Energy Consumption

Based on the throughput analysis of the case with and without network coding the proportion of time a node is either sends, receives or idles is defined as:

$$i_S = T_{i\to} \quad (12)$$
$$i_R = T_{\to i} \quad (13)$$
$$i_I = 1 - (i_S + i_R) \quad (14)$$

The total average system power can be calculated based on the proportion of time a node is in a given state multiplied with the power consumption required for that state:

$$P = P_S(A_S + B_S + R_S) +$$
$$P_R(A_R + B_R + R_R) +$$
$$P_I(A_I + B_I + R_I) \quad (15)$$

Based on system power and the end-to-end throughput the system obtain, we can calculate the energy consumption per bit:

$$E = \frac{P}{T_{B\to A} \cdot C + T_{A\to B} \cdot C} \quad (16)$$

III. Measurement and Analytical results

In this section, we present and verify the results from our analysis with results from the measurement setup. The measurement and the analytical results are both based on the Alice and Bob scenario with three nodes. These are realized in two different test cases:

1) The ratio $X_B : X_A$ is 4:5.
2) The ratio $X_B : X_A$ is 2:5.

A. Measurement and Analytical setup

In this subsection, we present the setup which is used to conduct the measurement and analytical results.

The measurement setup consists of three OM1P routers from Open-Mesh Inc. representing the nodes (A, B and R). Each node is configured to run CATWOMAN on top of a standard installation of the B.A.T.M.A.N-adv routing protocol. We refer the interested reader to [9], [10] for a more detailed description of this configuration and installation. The installed nodes were placed in different office rooms with R in the middle, see Figure 2. Nodes A and B are configured such that they are not able to directly communicate with each other hence, forced to use R.
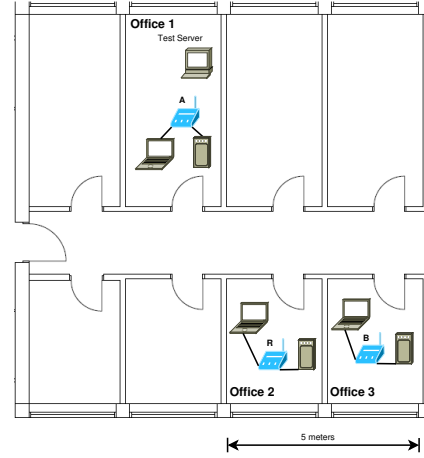

Fig. 2: Test setup in three different office rooms all located at the same level. Node A is placed in office 1, R in office 2, and B in office 3. Each node is attached to an energy measurement tool and a laptop. The laptops are connected to the local Ethernet. The Test Server is placed in office 1.

As shown in Figure 2, each node is connected to a laptop and an energy measurement tool. Each laptop at A and B generates and induces UDP data traffic into the connected node. The nodes transmit the induced data to R which re-transmits the received data to the intended receiver. Beside data generation, the laptops are also used to collect and store the received data from the energy measurement tool. The energy measurement tool measures the current by using a shunt resistor. The test case execution is handled by the Test Server which monitors and creates a test report. The test report contains information of the current test case. A selection from such report could for example be: the amount of data packets sent, received, lost and the power usage. This data is collected for a given data transmission rate coordinated by the Test Server. For example in Case 1, the induced data load at A would start from 100 Kbit/s to 5000 Kbit/s with a step size of 100 Kbit/s. Similar to A, the induced load at B would be 80% of the load induced at A, corresponding to a ratio of 4:5. The entire test consists of ten test runs per transmission and the duration of the entire test represents almost 23 hours. For each transmission step, we measure the current and data

throughput. Test Case 2 is the same as test Case 1, but the ratio $X_B : X_A$ is 2:5.

In order to plot our analytical expression and compare it with the measurement, variables such as the WiFi capacity C and the power values P_S, P_R and P_I need to be defined. These values are hardware specific, hence for the purpose of comparison these were measured on OM1P routers and presented in Table II. These values are then used in the equations presented in the previous section together with the induced load X_i similarly to the measurement setup. The involved equations are as follows: For throughput, Equation (8) and (11) were used and for power and energy, Equation (15) and (16) were used, respectively.

TABLE II: Measured Values

| Vatiable name	Measured value
C	7.2 Mbit/s
P_S	3.492 W
P_R	3.204 W
P_I	3.000 W

B. Results

In this subsection, we present the results for Case 1 and Case 2 for the approaches with and without network coding. These are shown in Figure 3, 4 and 5, where the solid lines represent analysis and the dashed lines measurement results.

The results for Case 1 are given in Figure 3 and 5a. Figure 3a and 3b shows the throughput for A and B for the two approaches as a function of the offered load. The measurement results are presented with 95% confidence interval. In these plots, it can be seen that the throughput for both approaches are increasing linearly with the offered load for the low load scenario. As the offered load increases, channel congestion and coding opportunities increases as well, leading to higher throughput for the approach with network coding. The same tendency also follows for the measurement results for the low load scenario. For the high load scenario the throughput for both approaches is lower than in the analysis. However, the measurement results stabilize when the induced load for A is around 3000 Kbit/s and for B 2400 Kbit/s which is also in line with the analysis.

Figure 3c shows the system power as a function of the offered load. It can be seen in the analysis and in the measurement results that the power value increases with the offered load for low load scenarios for both approaches. For high load scenarios the lines get stable for these two results. Furthermore, for both the analysis and measurement results, the approach with network coding has a lower power value for low load scenario than the approach without network coding and vice versa for high load scenario.
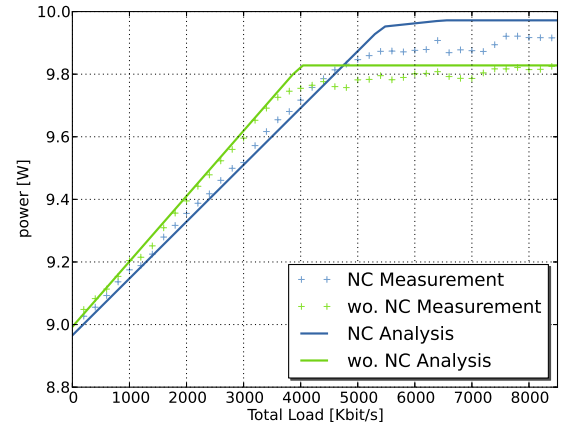
In Figure 5a, the system energy per bit plot is given. In this Figure it is shown that for low load scenarios the two approaches consume the same amount of energy. As for the high load scenario, the energy per bit stabilizes to a value of 4 $\mu J/bit$ and 2 $\mu J/bit$ for the approach without and with
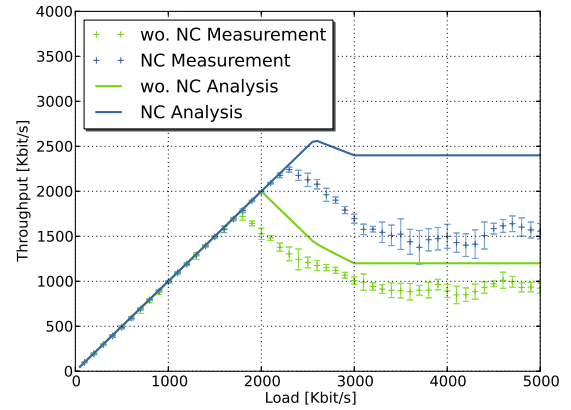
(a) Throughput Alice (A)
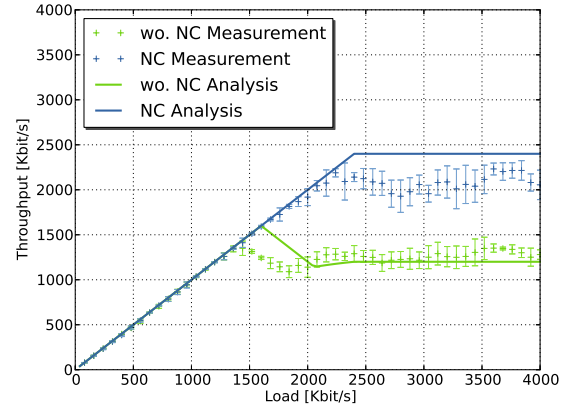
(b) Throughput Bob (B)

(c) System Power

Fig. 3: Case 1 with analytical (solid line) and measurement (dashed line) results. The notation *NC* represents the approach with network coding and *wo.NC* represents the approach without network coding

network coding for analysis. For the measurement results for high load scenario the energy per bit value stabilizes around 4.25 $\mu J/bit$ and 2.2 $\mu J/bit$ for the approach without and with network coding.

In the following, we present the results for Case 2. The results (analysis and measurement) for Case 2 are plotted

similarly to the results from Case 1 and these plots are represented in Figure 4 and 5b. Figure 4a and 4b show the throughput of A and B. Similar to Case 1 a linearly increasing tendency can be seen for the low load scenario. For the high load scenario a decrease in A's throughput is seen. Because of the large asymmetric data ratio (2:5) and a limited load range on the X-axis, the maximum channel capacity of B is not reached, hence only an increase tendency in B's throughout and a decrease in A's throughout is seen.

In Figure 4c and 5b, the system power and energy per bit plot is given. The tendency of these plots follow the same tendency of the equivalent plot in Case 1.

### C. Comparison of Analytical and Measurement results

In this section, we compare our analysis with the measurement results. In general our analysis and the measurement results fit very well. However, the measured throughput in Figure 3b, 4a and 4b is slightly lower than in analysis. In Figure 3a, we see an even larger difference between the analytical results and the measurement results. The first discrepancy is explained by the fact that the selected C for the analysis is based on an ideal measurement, in which the nodes were placed next to each other, while in the actual test case the nodes were placed in different office building leading to a lower maximum capacity. The difference in maximum channel capacity in the analysis and measurement explains the perfect fit for low load scenarios in Figure 3a, 3b, 4a and 4b in which we see that the channel capacity is not fully reached.

As for Figure 3a, the measurement results indicate that the throughput for the approach with network coding does not perform exactly as expected for high load scenarios. The explanations for this can be the link quality of one of the nodes being worse than the others which our analysis does not support. This leads to R likely choosing the node with the worse link quality to unicast the coded packet to, according to CATWOMAN. This means that the node with the better link quality will be neglected by R. From the measurement results in Figure 3a and 3b it is clear that the node with the bad link quality is A, hence the coded packet will most likely be transmitted or retransmitted to A leading to an increase in B's throughput. Moreover, the placement of node A also has an impact, as shown in Figure 2, the distance from R to A and B to R is not the same. Here it can be seen that B is closer to R than A is to R. However, the purpose with this measurement is to compare and validate our results from the analysis with real measurements that reflect a real life scenario and placing the nodes unevenly brings us more close to a real life scenario.

In Figure 3c and 4c the power value for both test cases are given. In these figures, it can be seen that both the analysis and the measurement results fit perfectly for low load scenario. It can also be seen that network coding transmits less packets as R combines two packets and transmit these as one, hence it requires less power usage than the approach without network coding. However, for high load scenarios both approaches have an equal transmission rate, but the receiving activity of
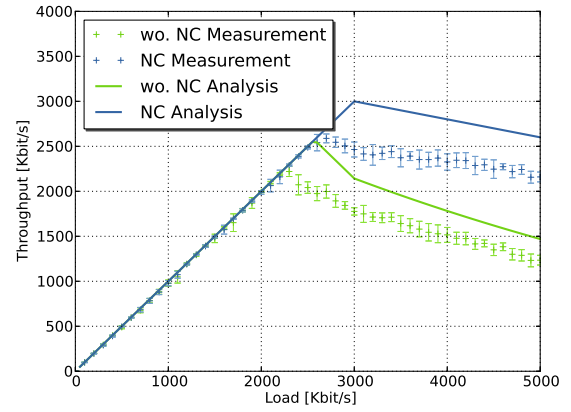
(a) Throughput Alice (A)
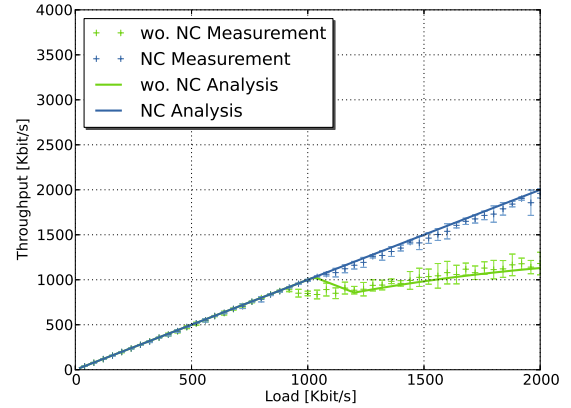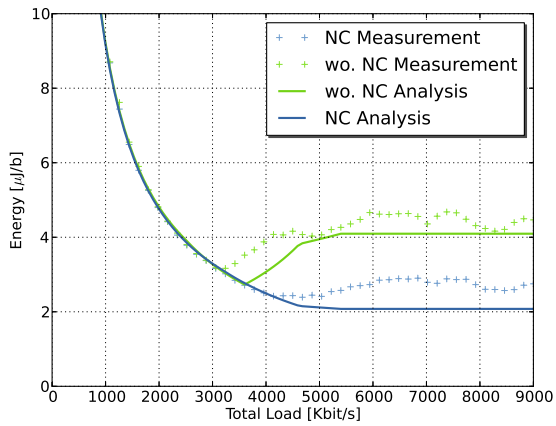

(b) Throughput Bob (B)
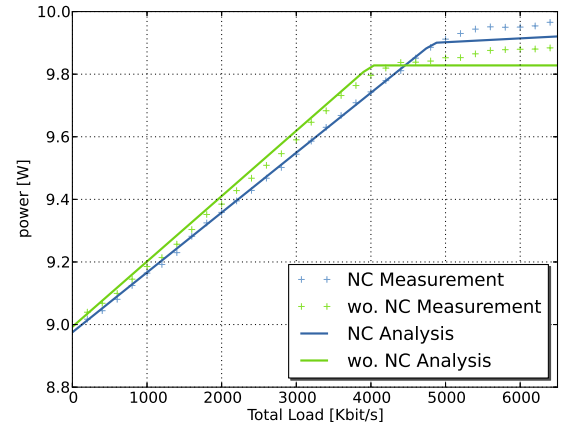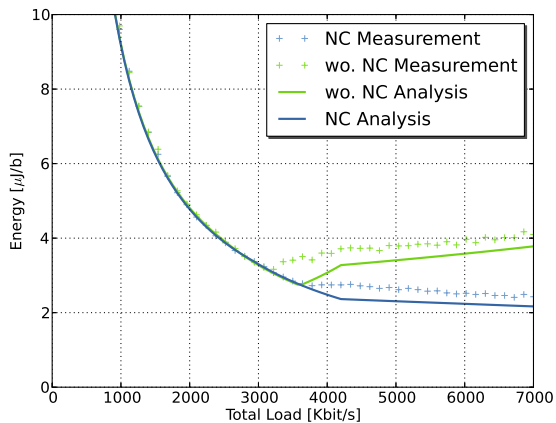

(c) System Power

Fig. 4: Analytical (solid line) and measurement (dashed line) results for Case 2. The notation *NC* represents the approach with network coding and *wo.NC* represents the approach without network coding

network coding is higher because each transmitted packet from R needs to be received and processed by both A and B. This leads to an increase in power for the approach with network coding.

In Figure 5a and 5b, we show the energy per bit for the analysis and measurement. We see that the results delivered

(a) Case 1: System Energy per Bit

(b) Case 2: System Energy per Bit

Fig. 5: Analytical (solid line) and measurement (dashed line) results for Case 1 and Case 2. The notation *NC* represents the approach with network coding and *wo.NC* represents the approach without network coding

here fit nicely. Both results predict the same energy per bit ratio for low load scenarios without any differences. However, for the high load scenario we see a slightly small difference for both test cases which is reflected from the deviation from the throughput. Regardless of the small deviation, the presented measurement results confirms the results from the analysis.

IV. Conclusion

In this paper, we investigated the asymmetric data traffic in a simple Alice and Bob scenario and presented an expression for the throughput and energy consumption for a wireless meshed network based on IEEE 802.11 technology. The results for the expression were then presented in two test cases, one with a large asymmetric data transmission ratio and the other one with less asymmetric data transmission ratio. These results were then compared and validated by means of real measurements.

The results show that even with asymmetric traffic, applying network coding saves energy for both low and high load scenario. For low load, we showed that for the approach

with network coding, less power is spent compared to an approach that does not support network coding. For the high load scenario, we see that the power rate for with network coding is slightly higher as each transmission from the relay has to be overheard by the other nodes in the network. But as the throughput is higher for the approach with network coding the energy per bit ratio is improving so that the gain per Joule is higher.

Previous works have verified that network coding saves bandwidth in case of high load and saves energy in both low and high load scenarios. However, this finding was based on the fact that the data transmission rate is symmetric. Our analysis demonstrate that network coding gives a benefit in terms of throughput and energy consumption even when the data transmission rate is asymmetric, and our measurement results confirm the results from our analysis.

V. Acknowledgement

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