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X-MalNet: A Novel Multi-Level eXplainability Framework for Malware Detection Using Matrix Product States (MPS) Tensor Networks

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We propose X-MalNet, an inherently explainable malware detection framework based on Matrix Product States (MPS) tensor networks. Unlike previous explainability methods that provide fragmented insights, X-MalNet natively generates multi-level explanations from a single coherent architecture. The MPS explicitly learns the joint probability distribution of features and labels, enabling faithful explanations through tensor operations. For binary classification, we model predictions via conditional probability $P(\text{malware}|\mathbf{x})$. From its core tensor decomposition, we derive: (1) exact first-order feature importance scores; (2) second-order feature interactions quantified via the entanglement spectrum from Schmidt decomposition, revealing non-linear logical dependencies; and (3) minimal, precise rule-based explanations extracted analytically by fixing feature values and marginalizing the network. Our preliminary results on the binarized EMBER dataset demonstrate impressive detection performance and capable of providing a holistic suite of faithful explanations without compromising performance.

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